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BLACK-AND-WHITE INFRARED FILM FOR COLOR PHOTOGRAPHY

Gershon Goldberg

FOREWORD

This report (TO-B 71-9) was prepared by Technical Operations, Incorporated, Burlington, Massachusetts on Air Force Contract F33615-70-C-1099. The contract was initiated under Project No. 6272, "Black and White Film for Color Photography." The work was administered under the direction of the Air Force Avionics Laboratory, Aeronautical Systems Division (AFSC), with Mr. James C. Pecqueux as Project Engineer. The studies presented here began on 1 November 1969 and were concluded on 31 March 1971.

Dr. Gershon M. Goldberg was Project Director for this contract. Mr. Stephen Farrell performed the sensitometric studies, and Messrs. Jack Willis and Robert Olsen handled the exposure, processing, and duplicating work. Mr. Richard Wilkins was responsible for the diffractometry, and Mrs. Alice Smith made densitometric and microdensitometric measurements. Mr. Robert Lindstrom prepared the dye-containing tricolor gratings, Mr. Robert Whitney prepared the infrared cutting dichroic filters, and Mr. Peter Mueller and Mr. Richard Powell were responsible for the design and fabrication, respectively, of the dichroic tricolor gratings. This report was submitted by the author on 31 March 1971.

This technical report has been reviewed and is approved.

Albert W. Berg

A.W. Berg
Photographic Branch
Reconnaissance Division
Air Force Avionics Laboratory

ABSTRACT

An attempt was made to use black-and-white infrared films as recording media for color scene information. The desired format for field use was a 5 inch tricolor striped film. Since current films are designed primarily as infrared receptors, their sensitivity balance was unsuitable for three color recording. In addition, their resolution proved too low for adequate modulation by a 40 ℓ/mm carrier. The latter limitation prevented experimentation toward a striped film because the present film striping system operates at 40 ℓ/mm. Investigations conducted with 30 ℓ/mm tricolor encoding gratings showed that the green, red, and infrared response of the films could be balanced in such a manner that all three spectral bands could be recorded at the same exposure level. Outdoor exposures indicated that the balancing filters reduced the speed of the film to an effective ASA of about 60. Because of the low resolution capability and high granularity of the infrared films, their latitude for recording 30 ℓ/mm modulated imagery was poor. When color imagery was retrieved from positive transparencies (prepared by duplication from the original modulated negatives), it proved to be of low saturation and exhibited a high level of grain noise.

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SECTION I

INTRODUCTION

Several years ago Technical Operations, Incorporated developed a new system that allows the recording of color imagery on commercially available black-and-white film. This system, which provides a color output without requiring costly and complex color processing, has features that make it potentially more useful than conventional color photography in field reconnaissance situations. On Contract F33615-69-C-1084, Tech/Ops investigated the use of extended red panchromatic aerial reconnaissance films as color recording media and showed that color scene information could be reconstructed from positive transparencies prepared by contact printing from the original modulated negatives. For ease of utilization in 5 inch aerial cameras, the format desired was one in which the color encoding filter was an integral part of the film surface. Accordingly, gravure printing techniques developed on Contract F08606-68-C-0052 were used to provide a 5 inch web of striped Kodak Plus-X Aerecon film 8401. The striped film was slit to a smaller size and its color-recording capability was demonstrated.

The initial objective of the present contract was to extend the concept of color recording on black-and-white film to current infrared films. As before, the ultimate intention was to provide a striped infrared film for use in 5 inch aerial reconnaissance cameras. The film was to have an effective aerial exposure index of at least 50 with a high contrast resolution of at least 25 line and space pairs per millimeter. Its color recording characteristics were to be similar to Kodak Ektachrome Infrared Aero film 8443. Because current black-and-white infrared films are designed primarily as infrared receptors, it became apparent early in the program that the imbalance between the green, red, and infrared sensitivities exceeded the dynamic range capabilities of the system. Although commercially available filter combinations could be used to balance the three sensitivity regions, standard filters do not have proper characteristics to correct the film without an excessive speed loss.

Our first approach to an alternative solution to the imbalance problem was an attempt to select three random spectral bands (covering the region between 500 and 900 nanometers), each being sufficiently wide to ensure equivalent film sensitivity. This could not be done without two of the bands being in the infrared. Such a system suffers from redundancy because the near infrared reflectivity of most objects does not tend to peak sharply but has a rather broad maximum spanning the 700 to 900 nanometer region. Thus, two of the color channels carry the same information, and we do not achieve the desired three channel reconstruction. The second approach, which proved more fruitful, was to prepare dichroic color balancing filters with properties matched directly to the film characteristics. In this way sensitivity losses were held to a minimum and the film could be used at a reasonable camera speed.

The achievement of a balanced response did not ensure the reality of a striped infrared film. Exposure tests with tricolor gratings in modified cameras helped to define the problems that must be solved before film striping can be considered. The

tests indicated that requirements for the color modulating dyes are more stringent in this case than they are for standard panchromatic films. The most serious problem arose in connection with the infrared absorbing dye which, at concentrations needed for adequate modulation, exhibited considerable broadening of its spectrum. In addition, the resolution of Kodak Infrared Aerographic film 2424 proved too low to allow reasonable color recording characteristics at a 40 ℓ/mm frequency. When carrier frequency is lowered from 40 ℓ/mm, the final system resolution falls below the desired limit of 25 ℓ/mm. Since present masters for printing cylinder fabrication are ruled at 40 ℓ/mm, lower frequency cylinders cannot be made until new master rulings are cut. The generation of these rulings is expensive and time-consuming. In view of the problems encountered, the expenditure needed to provide a striped infrared film cannot be justified unless a new infrared film with a better balance and improved resolution is forthcoming. Apparently, the best way to demonstrate the utility of recording color imagery on Kodak Infrared Aerographic film 2424 is by using tricolor gratings in modified cameras. Improving the overlap characteristics of the dyes presently used in tricolor gratings would be difficult. Therefore, for the final phase of this program we turned to newer gratings that utilize dichroic blockers instead of dyes to modulate the colors. Dichroic filters can be tailored to produce sharp spectral bands with a minimum of overlap and should provide the best color recording capability.

This final report details the experimental work carried out in the attempt to find a viable way of using black-and-white infrared film for color photography. Studies incidental to the main task, such as duplication from modulated negatives and sensitometric evaluation of modulated negative and positive transparencies, are also described.

SECTION II

DISCUSSION

FILM CONSIDERATIONS

Just prior to the inception of this program both Kodak aerial and amateur infrared films were changed. The new Kodak Infrared Aerographic film 2424 and Kodak High Speed Infrared film 2481 are thin, hardened emulsions coated on a 4 mil Estar base. The data sheets for the films indicate that their photographic properties are identical. Sensitometric tests conducted in these laboratories confirmed that the films could be used interchangeably. During the course of the program, we worked primarily with 2481 for two reasons. First, 2481 was more readily available and we were able to get faster delivery on this material. Second, 2424 does not come in sizes narrower than 70 mm. The equipment available for use at Tech/Ops requires 35 mm film, and it is necessary to slit and perforate the 70 mm stock. Not only is this a wasteful procedure, but also infrared film suffers handling damage more readily than other films and fog level variations and static markings are often introduced at this stage.

Three properties of the available infrared films were of concern at the start of the program. First, the resolution figures quoted by Kodak,[1,2] 80 ℓ/mm for a high contrast (1000:1) target and 32 ℓ/mm for a low contrast (1.6:1) target, place a limitation on carrier frequency that makes realization of the desired 25 ℓ/mm in the final color system difficult. Second, integration of the area under the spectral sensitivity curve published by Kodak[1,2] (see Figure 1) indicated that 8.9 percent of the film sensitivity is in the green, 21.5 percent in the red, and 69.6 percent in the infrared. This distribution makes the attainment of a spectral color balance difficult and requires that we sacrifice film speed in the infrared to achieve it. Third, the rms granularity value of 38 is high enough that we can expect scattering from the developed silver to add background noise to the imagery. These potential problems were pointed out in our proposal, and they will be discussed in more detail here.

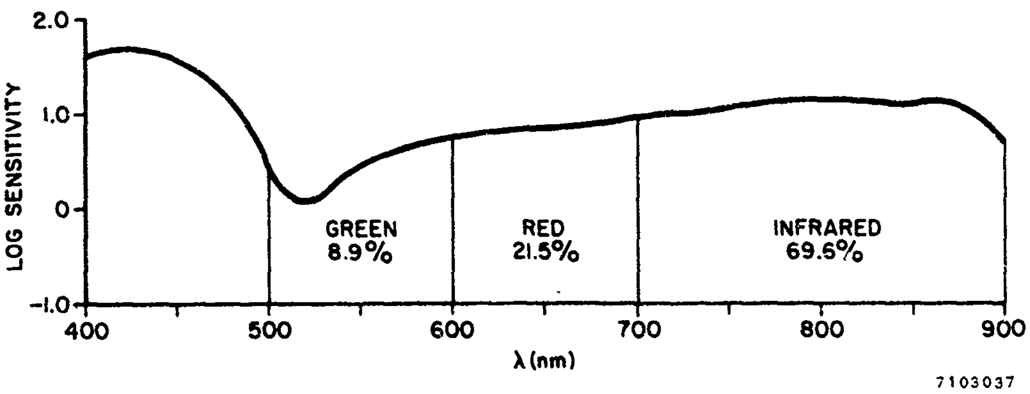

Figure 1. Spectral Sensitivity Distribution of Kodak Infrared Emulsions (2424 and 2481)

Resolution

In a system where the imagery reconstructed arises solely from the color channels (diffracted light), the resolution cannot exceed a value of half the carrier frequency. If the dc signal is superimposed on the reconstructed color image, the resolution value has been found experimentally to lie between 60 and 70 percent of the carrier frequency. Thus, to achieve 25 ℓ/mm the minimum carrier frequency would have to be 36 ℓ/mm. For good modulation the film resolution cutoff should be at least three times the carrier frequency; for the desired end properties, we need a film that has a cutoff resolution of about 120 ℓ/mm. The consequences of operating with a lower cutoff/carrier ratio are weak modulation and a narrowed exposure latitude.

A further complication is introduced by the need to process the film to a gamma slightly less than 1.0. Work on the previous contract had shown that optimum results were obtained by processing the negative to a low gamma and duplicating on a relatively high gamma film. Under these conditions we would use the film at a resolution level more nearly approximating its low contrast resolution (32 ℓ/mm). For these reasons we operated with a 33 ℓ/mm carrier at the beginning of the program and later lowered the frequency slightly to 30 ℓ/mm. This automatically limited the system resolution to a value of 20 ℓ/mm or lower.

Film Speed and Color Balance

Kodak Ektachrome Infrared Aero film 8443 was chosen as the comparison standard for the infrared color receptor to be devised on this program. Exposures of color targets on the Ektachrome indicated that its latitude was, at best, two stops. The color sensitivity values obtained by integrating under the Kodak curve for 2424 showed a three stop difference between green and infrared spectral regions. Because of the limited resolution of the black-and-white infrared films and the nature of their sensitization, we did not expect them to have greater latitude than the Ektachrome Infrared Aero film. The use of balancing filters during exposure was therefore essential.

The sensitivity curves published by Kodak for their Ektachrome Infrared Aero film 8443 indicate that the emulsion layers that record the green and the red light are of approximately equal sensitivity whereas the infrared recording layer has a slightly lower sensitivity. Our experimental results with the Ektachrome confirm the Kodak data. If we assume that the black-and-white film will have the best latitude for color recording if its green, red, and infrared bands are of approximately equal sensitivity, we can estimate the potential speed level of the final color balanced receptor. Taking the oversimplified view that the relative sensitivity values obtained by integration represent the contribution of each color to the total film speed, which in the case of 2424 is expressed as an Aerial Exposure Index of 100,[1] we arrive at a figure of 8.9 for exposure index to green light, 21.5 for exposure index to red light, and 69.6 for exposure index to infrared energy. A perfect balancing filter that subtracts no green and reduces the other exposures to the same level as the green should allow us to use the film at an Aerial Exposure Index of about 27 (3 x 8.9).

Granularity

The color system under study depends on the diffraction of light from modulated imagery to separate the effects of the individual color exposures. Diffraction can also take place at any edge where there is sufficient contrast. In a fast emulsion of large grain size the developed silver specks are large enough to diffract light and cause the superimposition of a grain pattern on the reconstructed color image. The Plus-X Reversal film used in current operating TOC systems has an rms granularity of less than 20, and we have found experimentally that films with rms granularity values much in excess of 20 exhibit grainy reconstructed images. Therefore, with a film having an rms granularity of 38, grainy pictures can be expected.

Summary

In weighing the various factors involved in using the current black-and-white infrared films for storage of color imagery, we have concluded that, at best, the film can have an aerial exposure index in the vicinity of 25 and a resolution between 15 and 20 ℓ/mm. In addition, since the rms granularity of the black-and-white films considerably exceeds that of the Ektachrome Infrared Aero film (38 versus 22), the reconstructed false color imagery will be grainier in appearance than the false color imagery of the Ektachrome.

CARRIER FREQUENCY CONSIDERATIONS

Since we were faced with the prospect of using a film intended primarily as an infrared receptor for a tricolor receptor, we first sought to determine whether the sensitivity imbalance could be handled to any extent without resorting to the use of light-balancing filters. Sequential exposures through green, red, and infrared isolation filters with the film in contact with a 40 ℓ/mm carrier indicated that the exposure latitude for the worst color was only one-third of a stop. To record all colors, therefore, the sensitivities of the individual color bands would have to be balanced within this limit. This restriction is too severe for practical photographic purposes, and the 40 ℓ/mm carrier frequency is obviously too high for the film's resolution capability. By lowering the carrier frequency to 33 ℓ/mm, the latitude is increased to a stop and a half. Later in the program a frequency of 30 ℓ/mm was adopted to bring the latitude to the same range as that of the Ektachrome Infrared Aero comparison film (approximately two stops).

FILTER CONSIDERATIONS

Color Balancing Filters

The latitude of the infrared film as used for color recording is less than the maximum sensitivity imbalance. Therefore we require a means of equalizing the sensitivity of the three color bands. Even though some degree of balancing can be achieved by departing from a 1:1 line-to-space ratio in the carrier, we would only recommend this

approach for relatively minor corrections. In the present situation, the use of color filters over the lens of the taking camera offers the best solution. Commercially available filters offered by such manufacturers as Kodak (Wratten) and Corning most frequently satisfy requirements similar to ours. For the particular system under study, however, these filters proved inadequate on several counts. Of the infrared-absorbing filters offered by Corning,[3] only the 1-57 and 1-56 absorb enough radiation between 700 and 900 nm to be useful. The ligher of these filters (1-57) has an average transmittance of less than 60 percent in the green. Experimentally the darker of the two gave the best photographic result when the 2424 film was exposed in a modified camera in contact with a tricolor encoding grating. The speed level of the optimum exposure was slightly under ASA 1, however, which seriously limits the usefulness of the system.

An inquiry to Kodak on infrared-absorbing filters brought the suggestion that Pittsburgh Plate Glass Company's heat-absorbing phosphate glasses #2043 and #9844 were better than any available Kodak filters for our specific requirement. Curves for these glasses in 2 mm thickness are shown in Figure 2. Calculations based on these curves indicated that a 5 mm thickness of the #2043 glass could bring the green and infrared speeds into balance. However, since the phosphate glass does not filter out enough red light, the red speed would be almost a stop faster. A cyan color-compensating filter can be used to reduce the red exposure to the proper level, but the red exposure cannot be reduced without further slight reductions in the amount of green and infrared light passing through the filter combination. In the end, although the speed loss is small compared to a filter pack utilizing the Corning infrared cutting filters, the potential exposure index (close to 20) is 30 percent lower than the previously calculated theoretical value (27). We, therefore, tried to minimize the speed loss by preparing dichroic filters matched specifically to the film characteristics.

Two types of dichroic filters were prepared. The first type subtracted infrared and some red. The second type was minus blue filters, cutting more sharply than a Wratten 12. The filter combination shown in Figure 3 was used for most of the later work on the contract. The filters in combination with the film provide a system with 34 percent of its sensitivity in the green, 35 percent in the red, and 31 percent in the infrared. The area under the filter-corrected sensitivity curve corresponds to an approximate exposure index of 32. This is higher than the value of 27 previously mentioned as a theoretical limit because the green band has been broadened from the normal 500-600 nm to 470-600 nm.

Color Separation Filters

In addition to the sensitivity-correcting filters, color separation filters were required to assess the sensitometric performance of the individual color bands. The Wratten filters normally considered for color separation work on panchromatic films are unsuitable for infrared work because both the Wratten 58 and Wratten 25

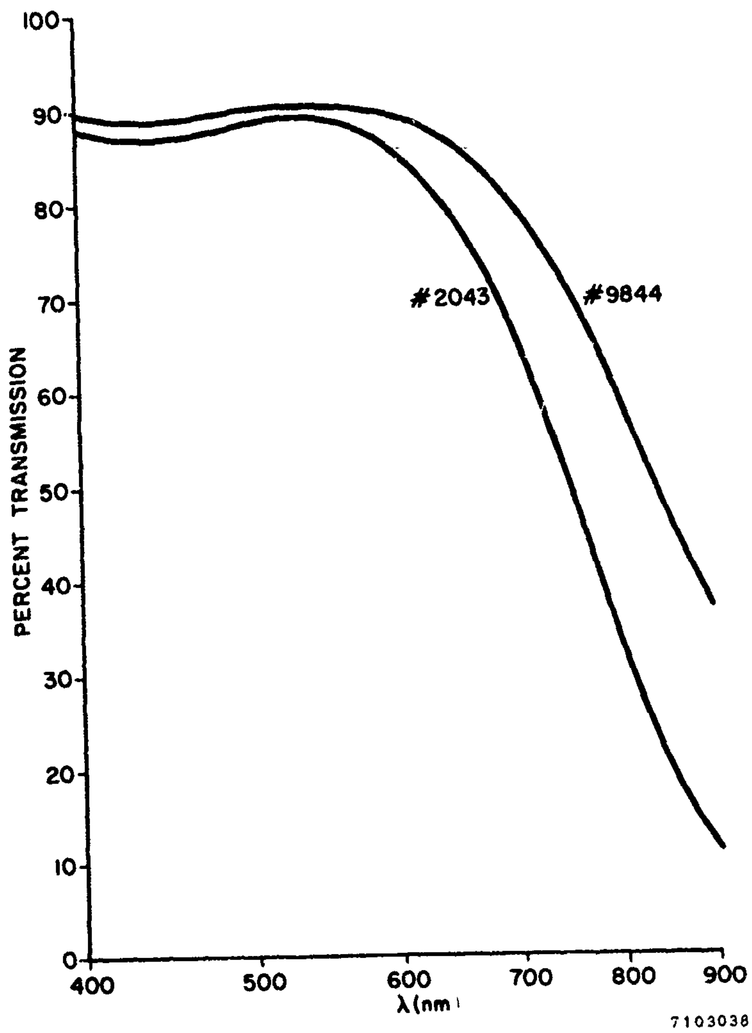

Figure 2. Spectra of Pittsburgh Plate Glass Infrared-Absorbing Phosphate Glasses

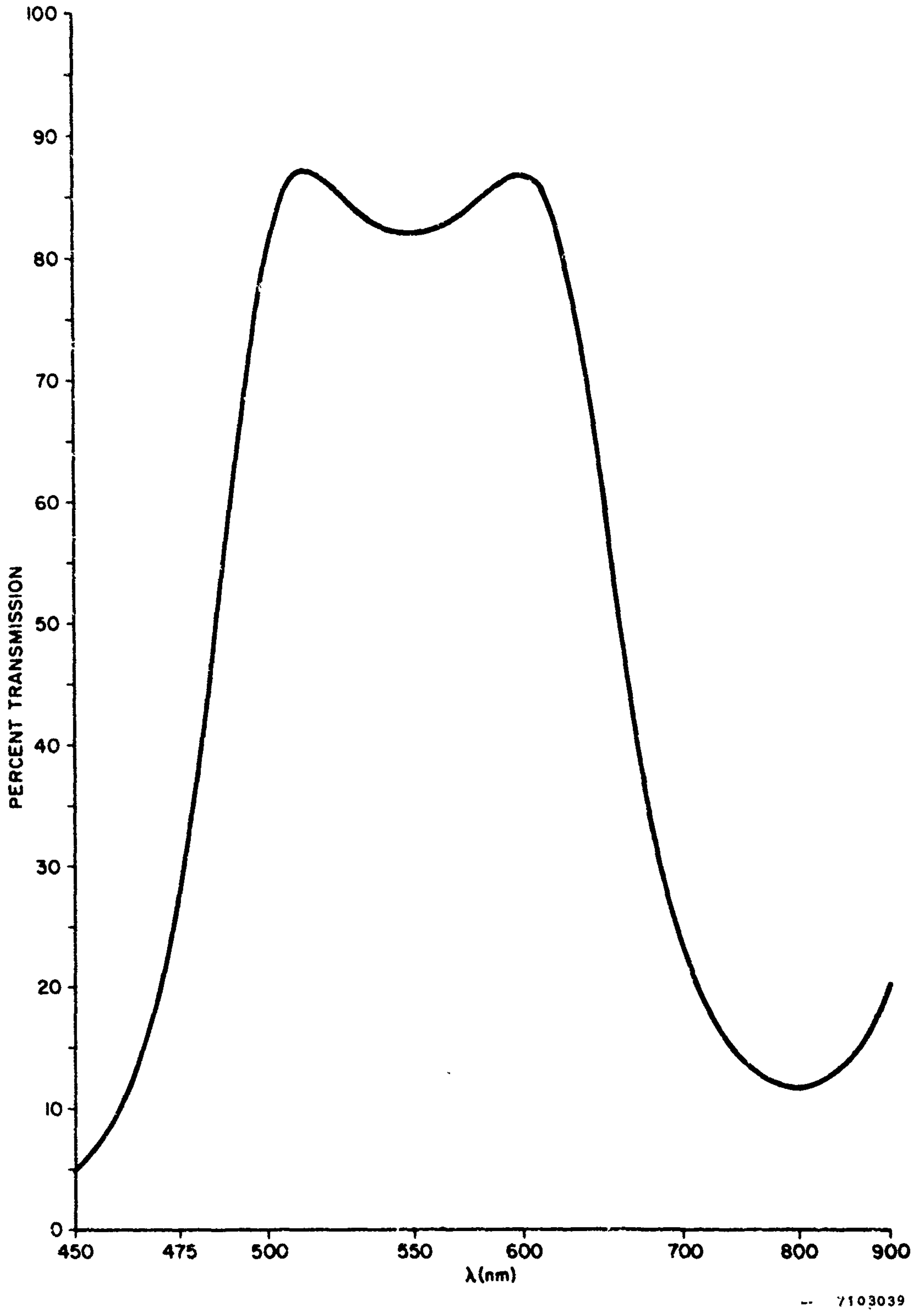

Figure 3. Spectrum of Dichroic Filter Combination, 66A Infrared and 9E Yellow

pass near-infrared radiation as well as their respective green and red bands. Two sets of separation filters were used during the course of the program. The first set, shown in Figure 4, was used by personnel at Wright Field for verifying the sensitivity distribution of the 2424 film. It consisted of the Wratten 58 plus Corning 1-56 for green separation, the Wratten 25 plus Corning 1-56 for red separation, and the Wratten 89B plus a 1.5 neutral density filter for infrared separation. The second set, shown in Figure 5, consisted of a Corning 4-76 blue green filter plus a Wratten 12 to subtract the blue, a red dichroic filter and a Wratten 89B. The first set of filters was used when we desired to correlate with the Wright Field work. The second set was preferred for sensitometric evaluations since the individual filters passed more light, and narrower camera lens openings could be used.

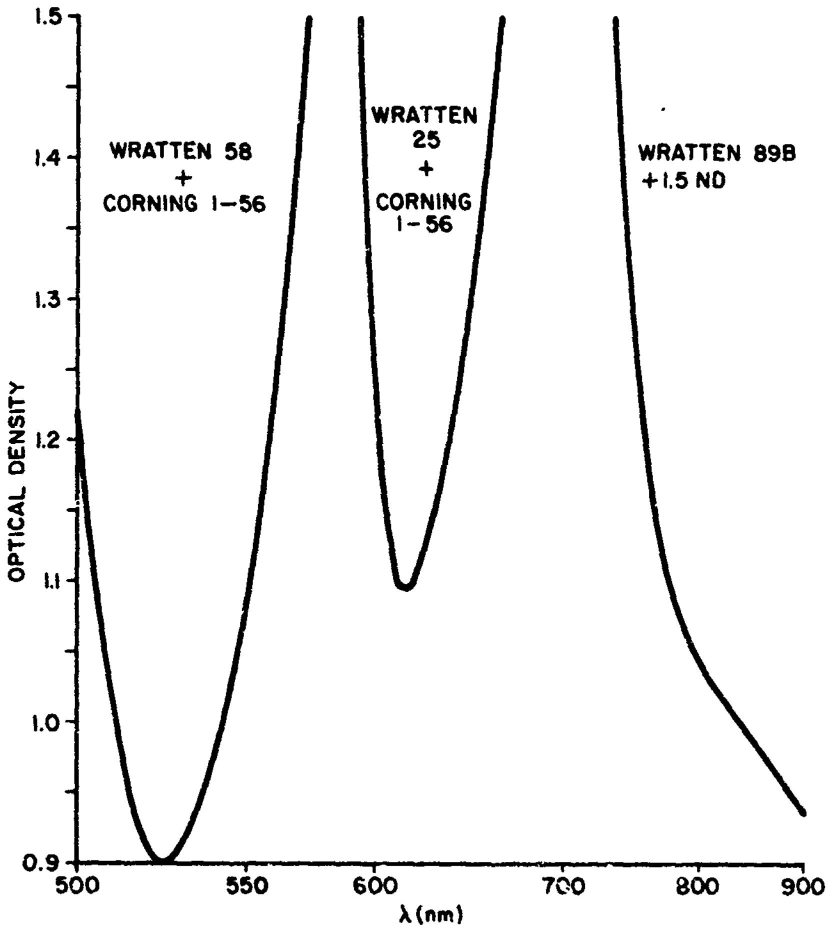

Figure 4. Color Separation Filters for Use with Infrared Films

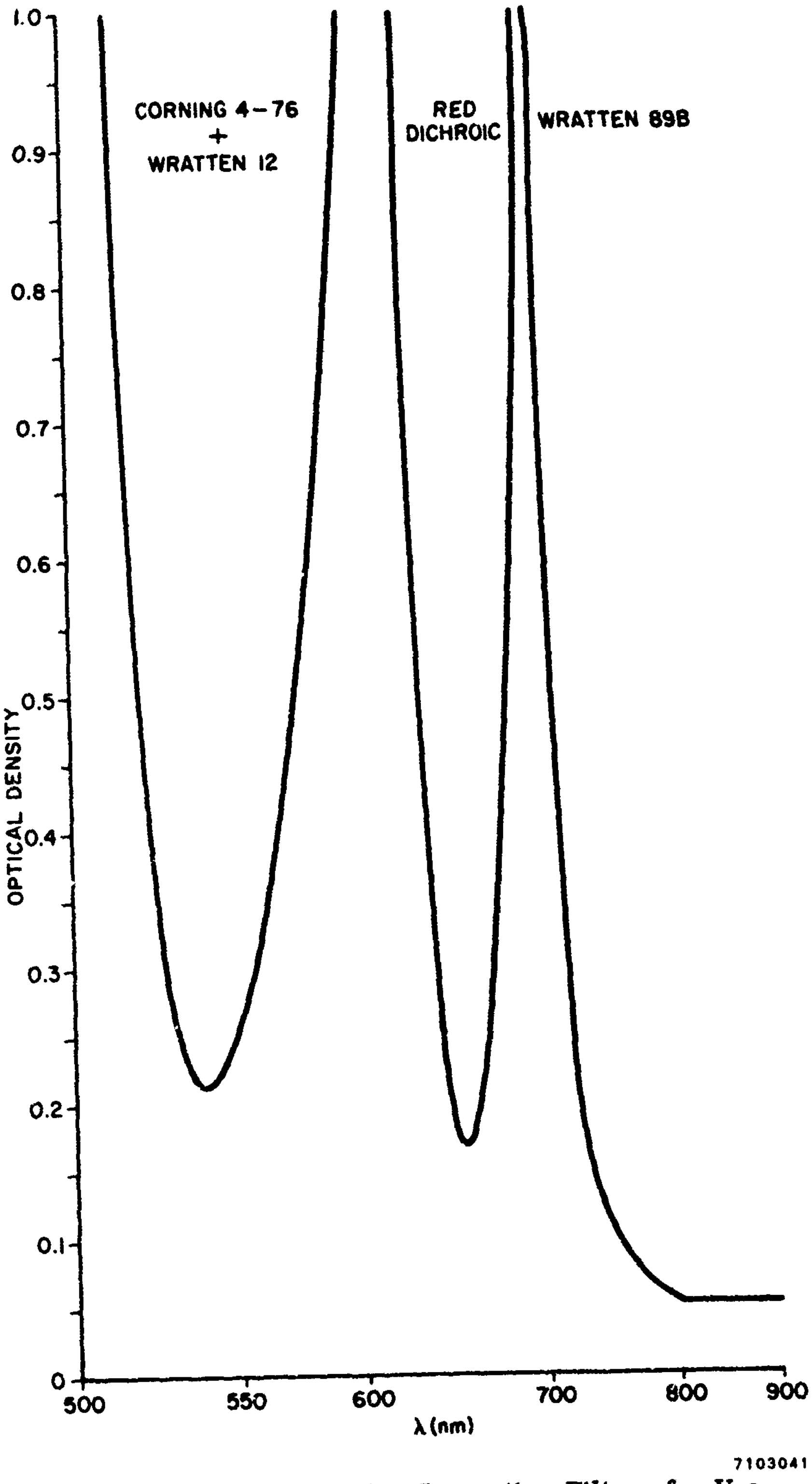

Figure 5. Alternate Color Separation Filters for Use with Infrared Films

FILM STRIPING CONSIDERATIONS

Various aspects of film striping as it pertains to infrared film have been mentioned in the previous discussion. Nevertheless, for the sake of clarification, we summarize here what needs to be done before striped infrared film can become a reality.

Printing Cylinders

The inability of the 2424 and 2481 films to hold a carrier frequency of 40 ℓ/mm prevented our using the present gravure cylinders to stripe either emulsion. The fabrication of cylinders capable of printing 30 ℓ/mm patterns should be simpler from an engraving point of view, and we might expect to achieve greater etch depths and correspondingly denser prints of the modulating lines. To reach the point where a cylinder can be engraved, however, a glass master ruling approximately 17.5 in. square with a 30 ℓ/mm pattern must first be engraved. Because of the vagaries of scribing so many long lines in a single, automated operation, many rulings must be made before the desired degree of perfection is achieved. The glass master is used to generate three 17 in. x 7 in. flexible copies of different angular orientations.

Again, because of the difficulty in making such large format contact prints, the operation has a high failure rate. The flexible masters, in turn, are used to expose photoresist-coated cylinders and produce the line patterns that are finally etched into the copper cylinder face. Thus they have a finite lifetime and must be replaced periodically. The cylinders themselves, even though they are chrome-plated after engraving to increase their durability, wear rapidly because of the fineness of the pattern and require frequent replacement. As a rough estimate, the cost of producing the 30 ℓ/mm printing system would have amounted to approximately half of the contract funding.

Printing Inks

For striping panchromatic film, yellow, magenta, and cyan inks are used. The spectra of the inks were shown in the final report on Contract F33615-69-C-1084 (Ref. 4, p. 26). The magenta and cyan inks have reasonable bandwidths for use with either the 2424 or 2481 film. The formulation of an infrared-modulating ink presents a problem in three respects. First, although many dyes are available commercially, the large-scale consumers have no requirements for infrared dyes. Therefore the few infrared-absorbing dyes that can be purchased are specialty items made in small quantity and sold for high prices. Second, long chain dyes that absorb in the near infrared are generally very unstable and tend to fade rapidly. Third, infrared-absorbing dyes at high concentrations, such as those required for the inks, have a strong tendency to desensitize or fog silver halides. Fortunately, our film striping work indicates that a desensitizing or fogging ink can be overprinted as the second or third set of stripes without affecting film properties.

The dye used in this work, Indocyanine Green, is the only commercially available infrared dye that has the necessary stability to qualify for use in an ink. However, it has two drawbacks. Being a cyanine dye it tends to form aggregates of differing composition as the concentration is increased. At the high concentrations present in a dried ink, its spectrum is considerably broadened and overlaps too strongly in the red spectral region. Also, it is difficult to synthesize and is presently available from only one supplier at a cost of $32.50/50 mg. Since a minimum of a pound is required to prepare a single batch of ink, the cost becomes prohibitive.

Summary

Since present black-and-white infrared films appear to be lacking in qualities necessary to provide adequate modulation -- that is, since they are marginal in resolution, granularity, and acutance -- we do not believe that the type of expenditure required for a film striping system is warranted until we can show, by other available means, that the films are capable of yielding practical photographic results.

TRICOLOR GRATING CONSIDERATIONS

For experimental purposes we were forced to use tricolor encoding gratings with magenta, cyan, and infrared-modulating dyes occupying the individual line patterns. After testing at 40 and 33 ℓ/mm we finally settled on 30 ℓ/mm as the operating carrier frequency.

Only one alteration was needed in the grating fabrication to accommodate the infrared dye. Normally, after an individual color is introduced, the glass plate that serves as a base for the grating is baked at an elevated temperature. This sets the vehicle and prevents smearing of the color in subsequent operations. As the thermal stability of the infrared dye was too poor to allow baking, the infrared lines were the last to be introduced. This meant that during camera exposures the infrared-modulating dye was closest to the film. From focus considerations it would have been better if the infrared line pattern were furthest from the film.

The first gratings prepared utilized the same magenta and cyan dyes that are used for standard panchromatic films along with Indocyanine Green as the infrared modulator. All the exposures made through these gratings were unsatisfactory since the reconstructed imagery never showed more than two colors; the green false color resulting from red light exposures was always missing. When the negatives were examined we noted that, regardless of exposure, there were never dense lines developed in the red direction. Since the lines develop in the open areas where there is no cyan dye to block red light, we concluded that the magenta and infrared dyes that crisscross the open areas of the cyan grating were absorbing too much red light. In other words, since red is the central spectral band in this system and tends to be overlapped by both side bands, it is important to limit the overlap. The overlap in the first gratings (Figure 6) was excessive because of a broadening of the spectrum

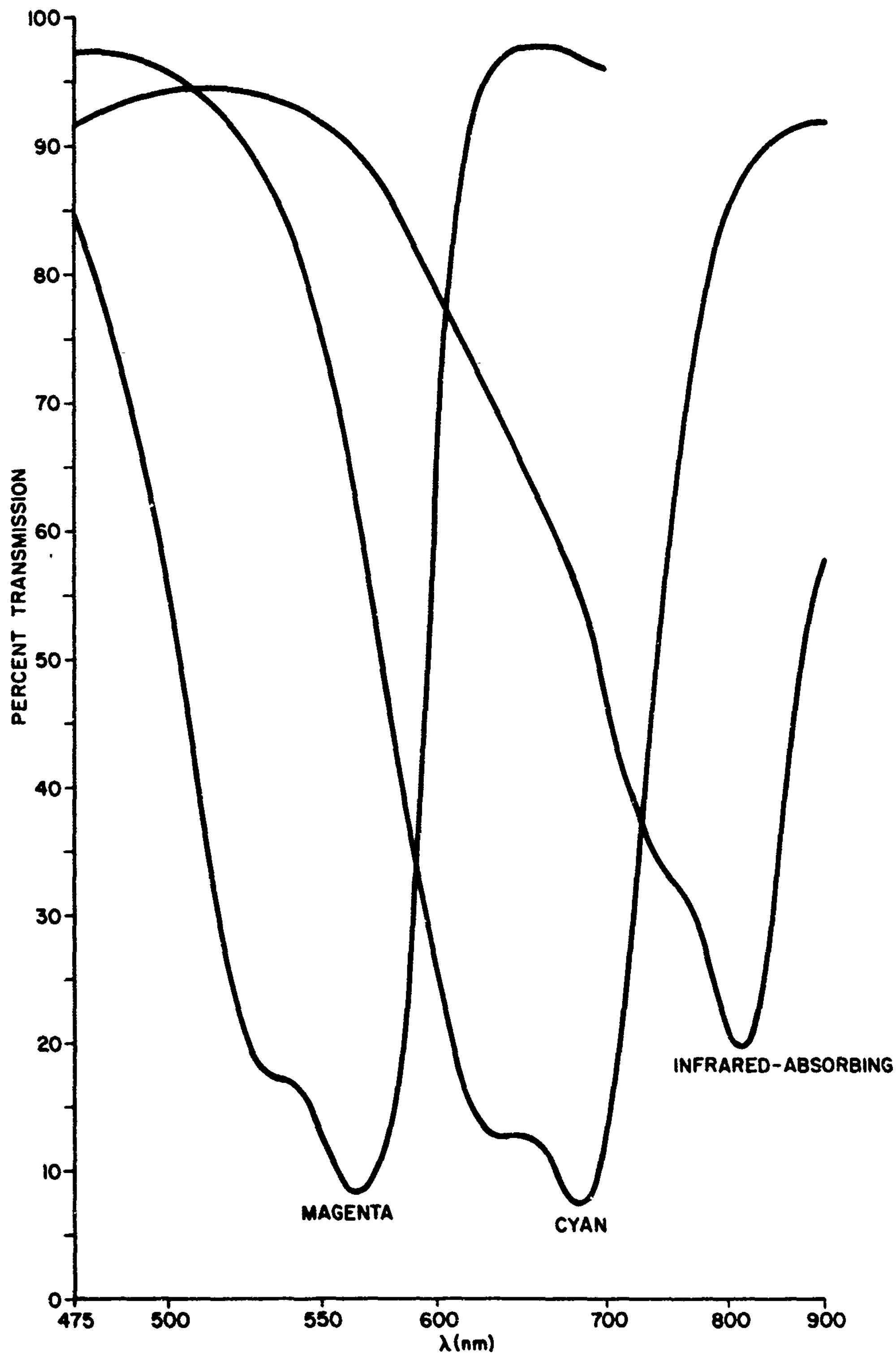

Figure 6. Spectra of Modulating Dyes Used in First Tricolor Gratings

of Indocyanine Green and the relatively broad spectrum of the cyan dye. The cyan dye used in the gratings is ordinarily not the same as the cyan dye used in the printing ink because an alcohol-soluble vehicle is used in the gratings whereas the inks are water-based. Because the water-soluble cyan does not overlap in the infrared, we prepared a final series of tricolor gratings with the alternate cyan. We were also able to narrow the spectrum of Indocyanine Green by adding an anionic polymer to influence its state of aggregation. The improved tricolor grating allowed us to record all three colors. However, the quality of the color imagery reconstructed from a positive dupe was not comparable to the quality of TOC imagery on panchromatic films.

The final attempts to generate color imagery of improved saturation utilized gratings in which the individual sets of lines were dichroic filters. The spectra of Figure 7 show the improved sharpness of the cutoff and the improved rejection characteristics for each individual color band. The results obtained were not equivalent to those obtained with the final series of chemical gratings.

To protect the tricolor encoding gratings from damage within the camera, it is common to cement a very thin coverglass over the face of the completed grating. Exposures made with modified cameras containing both unprotected and cover-glassed gratings indicated that there was no measurable difference in the line quality produced on the negative from either grating. Therefore coverglassed gratings were used in most of this work. For our best result, the color target was photographed outdoors. The 2481 film was exposed in a modified Pentax camera containing the coverglassed 0-66-2 grating (described later in the experimental section) for various times at a fixed f-stop (f/11). According to the light meter in the camera the optimum frames were exposed at ASA speeds between 40 and 80. Figure 8, a photomicrograph of a neutral patch on the film, shows the presence of all three modulation directions.

SENSITOMETRY

General Considerations

One of the secondary objectives of the contract was to devise a sensitometric system applicable to the analysis of the modulated imagery from which the false color is retrieved. During the first few years of work on the TOC system, no attempt was made to work out a sensitometric procedure because of the general complexity of the task. Diffraction from modulated imagery is, in itself, not simply dependent on one single factor. Although the difference in density (ΔD) between a line and the adjacent space has bearing on the extent of the diffraction, the ratio of the width of the line to the width of the space also is important. When ΔD and line density are low, a large portion of the diffracted energy can originate from the phase image formed by localized tanning of the gelatin adjacent to the developing image.

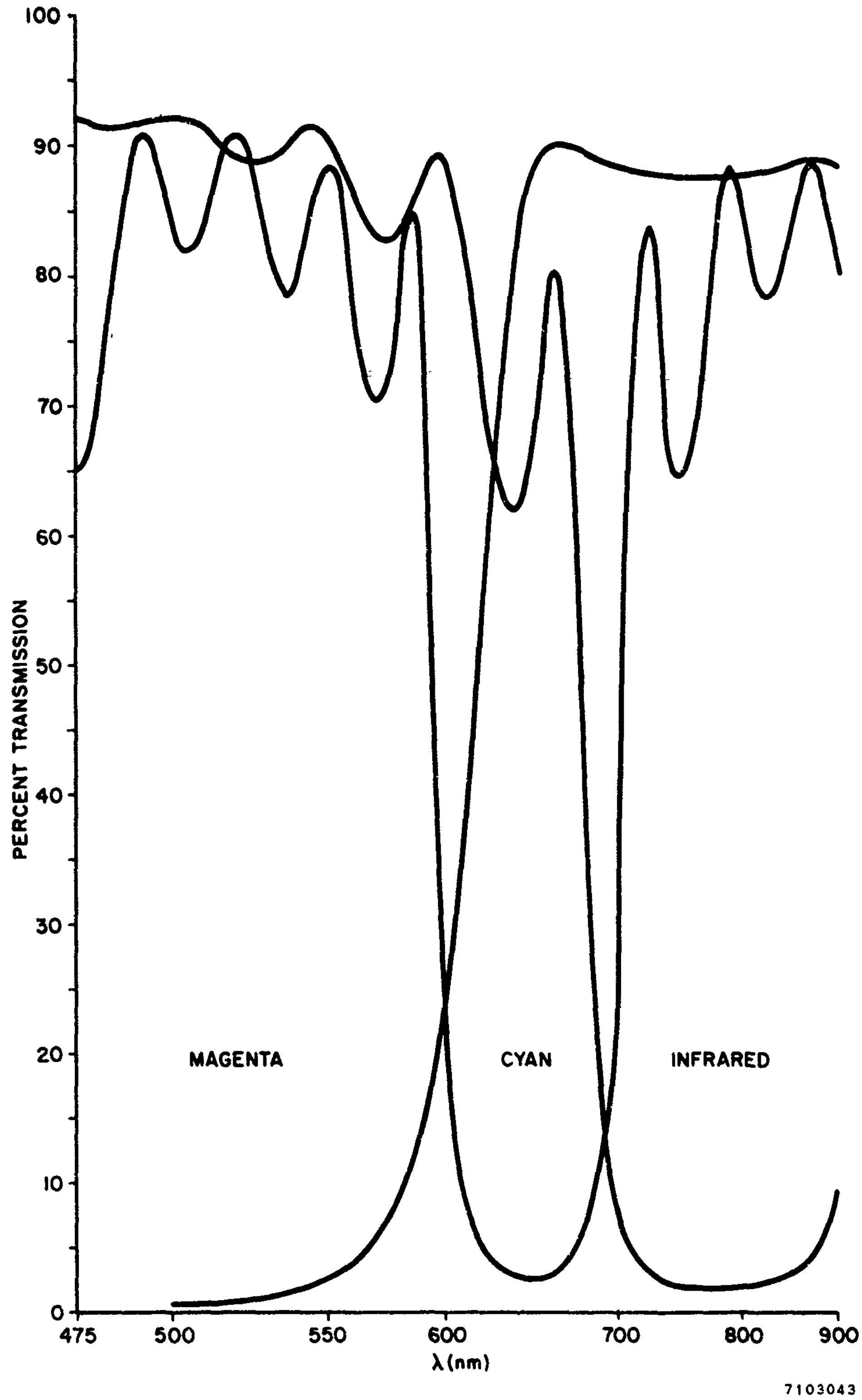

Figure 7. Spectra of Modulating Dichroics in Dichroic Tricolor Grating

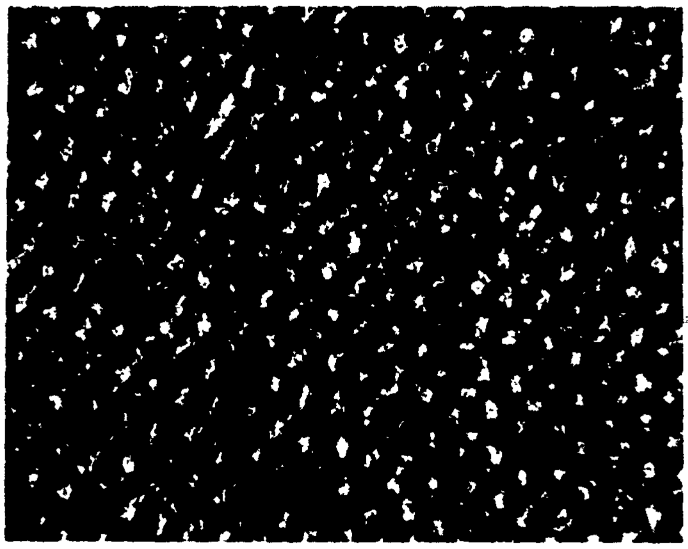

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Figure 8. Photomicrograph Illustrating the Presence of All Three Modulation Directions

The playback system itself introduces complications. Each color channel is continuously variable, and means are provided for superimposing a variable amount of dc energy. Since the density in the color channels is dependent on diffraction phenomena and the density in the dc channel is influenced by localized optical density variations of the black-and-white transparency, every different combination of color channel and dc channel settings will correspond to a different sensitometry for the individual film frame being viewed.

In recent years, a general system has been devised for evaluating modulated positive transparencies prepared directly by reversal processing of film exposed in TOC cameras. Flat gray fields are photographed through an exposure range. The resulting processed transparencies are evaluated in a diffractometer that measures the energy in each color channel. The plots of diffracted energy versus exposure for each color channel can be interpreted in much the same manner as an H and D curve. In addition, the effectiveness of the color separation can be measured from sequences of exposures made through color separation filters. Again, diffractometer measurements for each color channel lead to curves showing the response for the individual color compared to the other two. The separation between the curves parallels the color separation efficiency of the tricolor filter.

The general scheme of sensitometric analysis is complicated by two features of the system we have investigated on this contract. First, the fact that we are using an infrared film creates many problems. In addition, the fact that we process the

original camera exposures to a negative but view the reconstructed color imagery from a positive transparency generated from that negative adds further variables to an already complex picture. Both points are discussed here in more detail.

Special Requirements of Infrared Film

Light Source. For sensitometric evaluation of panchromatic films a tungsten light source corrected to a color temperature of 5500°K or 6000°K is commonly used. The correction filters take into account only the visible region of the spectrum (400 to 700 nm) and are not suitable for use with infrared materials. A standard has been proposed for an "Air Photo Daylight,"[5] and a filter combination suitable for correcting a 2854°K tungsten lamp was described in the same article. The tungsten lamps used in our sensitometric setup operate at 3200°K and would require a slightly altered filter pack. Since the suggested filter pack uses three filters with a combined thickness of approximately 11 mm and, since we already must use a minus blue filter and a dichroic color sensitivity balancing filter in front of the camera, we concluded that it would be simpler to devise a dichroic filter to correct our usable region (500 to 900 nm) to the Air Photo Daylight specification. The spectrum of the desired filter is shown in Figure 9. Because of other problems more important to the achievement of the primary objectives of the contract, we did not have sufficient time to generate this filter.

Filters and Color Patches. In the earlier section of the discussion dealing with filter considerations, we pointed out that normal color separation filters pass infrared as well as their visual color and we described substitute filter combinations. Neutral density filters also present a problem. The Wratten 96 series of filters do not have the same nominal density in the near-infrared as they do in the visible. For example, the 1.0 neutral density filter has a density of only 0.6 in the 750 to 900 nm region. The selection of a "neutral" gray patch for sensitometry thus becomes difficult unless means are available for determining its infrared reflectivity. The gray wedge that is included as a part of the color target we normally photograph under outdoor conditions has previously been used as the indicator of color balance. That is, when adjusting the relative amounts of each color in the reconstructor, we observe the gray wedge and adjust until it appears neutral. In the present case we cannot use this criterion because exposures on Ektachrome Infrared Aero film indicate that the steps of the recorded wedge are cyan in color. This is the color that would be expected if the infrared reflectivity of the wedge were low compared to its red and green reflectivity.

Color patches present a similar problem. Color patch targets have been photographed to document the ability of a TOC system to record primary and mixed colors over a range of exposures. Since the eye does not see infrared wavelengths, a true color cannot be assigned to the infrared band. Accordingly, the Ektachrome Infrared Aero film is set up in a false color configuration in which objects of high infrared reflectivity are reproduced in red tones, objects of high red reflectivity are reproduced in green tones, and objects of high green reflectivity are reproduced in blue tones. Selection of color patches yielding pure primaries is difficult

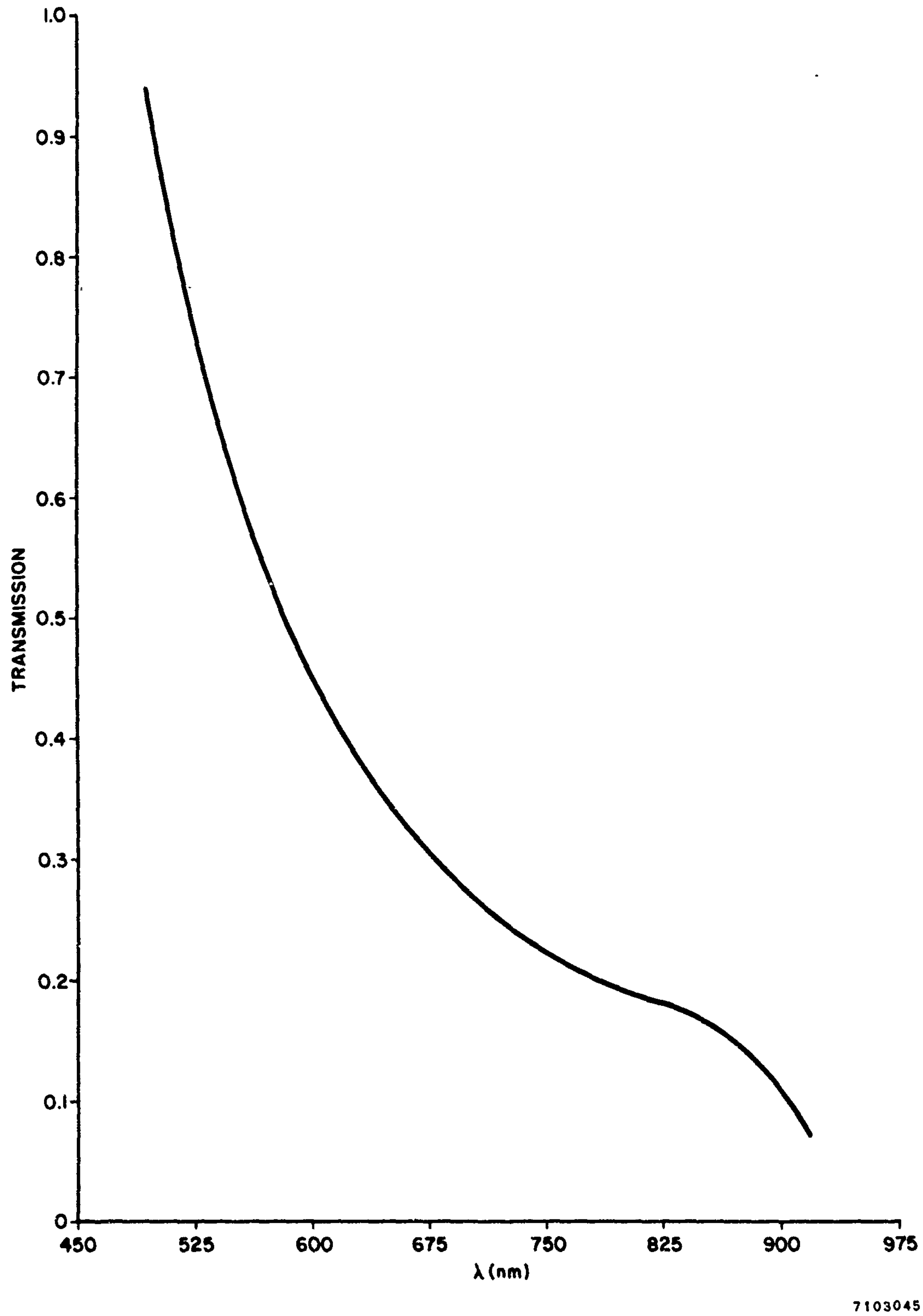

Figure 9. Spectrum of Filter Required to Correct 3200°K Lamps to Proposed Air Photo Daylight

because most dyed objects that reflect red light also reflect infrared to an equal or greater extent. For this reason the Ektachrome film was used to screen various color patches and determine which were suitable for use.

Evaluation of Negative Transparencies

The evaluation of the modulated negatives appears to be relatively straightforward. A sequence of exposures in a TOC camera to neutral patches yields a sequence of line patterns with varying line and background densities. Analysis in the diffractometer produces H and D type curves from which the tracking of the individual colors can be assessed and speed and gamma determined. Similarly, exposure through color separation filters yields another sequence of patches from which the separation of the colors can be measured. These data will indicate how well the color scene information has been recorded. Some degree of visual confirmation of the sensitometric measurements can be obtained by reconstructing the color from the negative under conditions where no dc channel is used.

The negative is primarily intended to be used as a rapid access black-and-white record, and the positive transparency generated from it will be the source of the reconstructed color imagery. However, it is important to determine the color sensitometry of the negative because, if the modulation on the negative is not sufficiently well defined, the preparation of a positive duplicate that yields satisfactory color will be impossible.

Evaluation of Positive Transparencies

The positive transparency from which the color imagery is reconstructed is difficut to analyze sensitometrically. Although the modulated patches used for sensitometry of the negative can be duplicated individually, the procedure would be time-consuming and subject to variations in exposure and processing.

As an example of the type of problem that can arise we cite the results obtained on duplicating color target images from two adjacent frames (one stop exposure difference) on a negative. The best color reconstruction on a positive transparency from the lighter negative frame was obtained when the duping film was exposed between 2.5 and 5 sec. The best color reconstruction on a positive transparency from the darker negative frame was obtained when the duping film was exposed between 5 and 10 sec. To simulate actual operating conditions where the negatives are the result of a single exposure and the duplicating conditions are adjusted to compensate for the quality of the negative, we would benefit if we could record an entire step wedge on a single frame of film. Then the duplication process would be simplified and exposure and processing conditions would be more uniform. Unfortunately, in 35 mm format the individual step size would be small enough to make the measurement process difficult.

MISCELLANEOUS STUDIES

At the beginning of the program, while we were awaiting the delivery of the 2424 and 2481 films, some dye sensitization experiments were conducted with High Speed Infrared film, Type 5218, to see whether its sensitivity to green light could be augmented. Erythrosin sensitized film showed an increase of a stop and a half in green speed at the optimum. However, when the new infrared films were obtained and the same procedure was tried, the dye solution did not appear to penetrate into the emulsion and no sensitization was observed.

Late in the program two attempts were made to see whether a film striping approach was feasible with current films. In one attempt, magenta and cyan inks were striped from the 40 ℓ/mm cylinders onto 2481 film. The striped film was exposed in a modified camera in contact with a 30 ℓ/mm Indocyanine Green grating. We tried this approach for two reasons. First, the resolution capability of a film often decreases as the wavelength of the exposing light increases, and we thought that the infrared film might possibly have higher resolution to green and red light than to infrared energy. Second, in this configuration the infrared modulating grating is furthest from the film which, from focus considerations, is the most desirable location. We were unable to get any reasonable line structure from the 40 ℓ/mm striped gratings.

The second approach tried was to see whether a panchromatic film could be sensitized to a reasonable level in the infrared. If this could be accomplished, selective sensitization by a printing technique could provide an effective grating of alternate infrared-sensitive and infrared-insensitive areas to complement the magenta and cyan gratings striped on the film by the normal printing process. The resulting film would have a better sensitivity balance and better resolution than the 2424 or 2481 film. Using the infrared sensitizing dye S-916 (Carbic-Hoechst) and Direct Positive Panchromatic film, we reached a maximum sensitivity level (measured through a Wratten 89B filter) two orders of magnitude above the infrared sensitivity of the untreated film. However, this level was still two orders of magnitude lower than the red or green sensitivity of Direct Positive Pan. On this basis the approach is impractical.

SECTION III

EXPERIMENTAL INVESTIGATIONS

Our experimental studies are presented here in a more or less chronological order. The technical difficulties encountered from the beginning of the program necessitated altering our objectives several times during the course of the contract. Therefore the work can be better understood if the individual phases are reported in the order in which they took place. The sensitometric studies, which were time independent, will be discussed apart from the other investigations.

ALTERATION OF SENSITIVITY DISTRIBUTION OF INFRARED FILM

The published sensitivity curves for Kodak Infrared films (see Figure 1) indicate that their green sensitivity is very low compared to their red and infrared sensitivity. Since exposure through a Wratten 25, 89B, or 87 filter is always recommended, we assumed that little effort had been made to impart green sensitivity to the emulsion. We hoped that sufficient green sensitizing dye could be imbibed into the emulsion to displace some infrared sensitizing dye. The resultant increase in green sensitivity at the expense of infrared sensitivity would help balance the relative color response of the film.

A 0.4 percent solution of Erythrosin B in water was prepared as a stock solution, and dilutions were made to concentrations of 2 g/liter, 500 mg/liter, and 100 mg/liter. Approximately 5 ft lengths of Kodak High Speed Infrared film, Type 5218, were wound on Nikor reels and dipped for 5 min in Nikor tanks containing the dye solutions. After drying, strips of each dyed length were exposed in the Tech/Ops Spectral Sensitometer to light passing a 520 nm dichroic filter (60 nm half-band width), and in a Tech/Ops black-box sensitometer to light passing a Wratten 87 or 89B filter. (The 520 nm filter peaks near the region of minimum film sensitivity.) The strips were processed for 8 min in D-19, rinsed, and fixed.

Films soaked at the highest dye concentration were heavily stained (magenta), had gained no green sensitivity, and had lost nearly all their infrared sensitivity. Beneficial results were obtained only with films soaked in the two lower concentrations of dye. The 500 mg/liter solution gave optimum results, which are summarized in the curves of Figures 10 and 11. The increased green sensitivity compared to the control (Figure 10) appears to be slightly over a stop. The loss in infrared sensitivity compared to the control (Figure 11) is more difficult to evaluate since the gamma values differ for the two curves. It is nevertheless far less than the gain in green sensitivity. What appears to be a fog increase on the dyed samples is primarily caused by a filter effect of the magenta stain on the film. When we consider that magenta subtracts green, the actual gain in green response may be greater than our tests indicated. We did make one attempt to reduce the staining effect of the dye on the gelatin at the film surface by taking a dry dyed strip and rinsing with alcohol before exposure. However, the gain in sensitivity on this test was less than we had observed for dyed strips not subjected to the alcohol rinse.

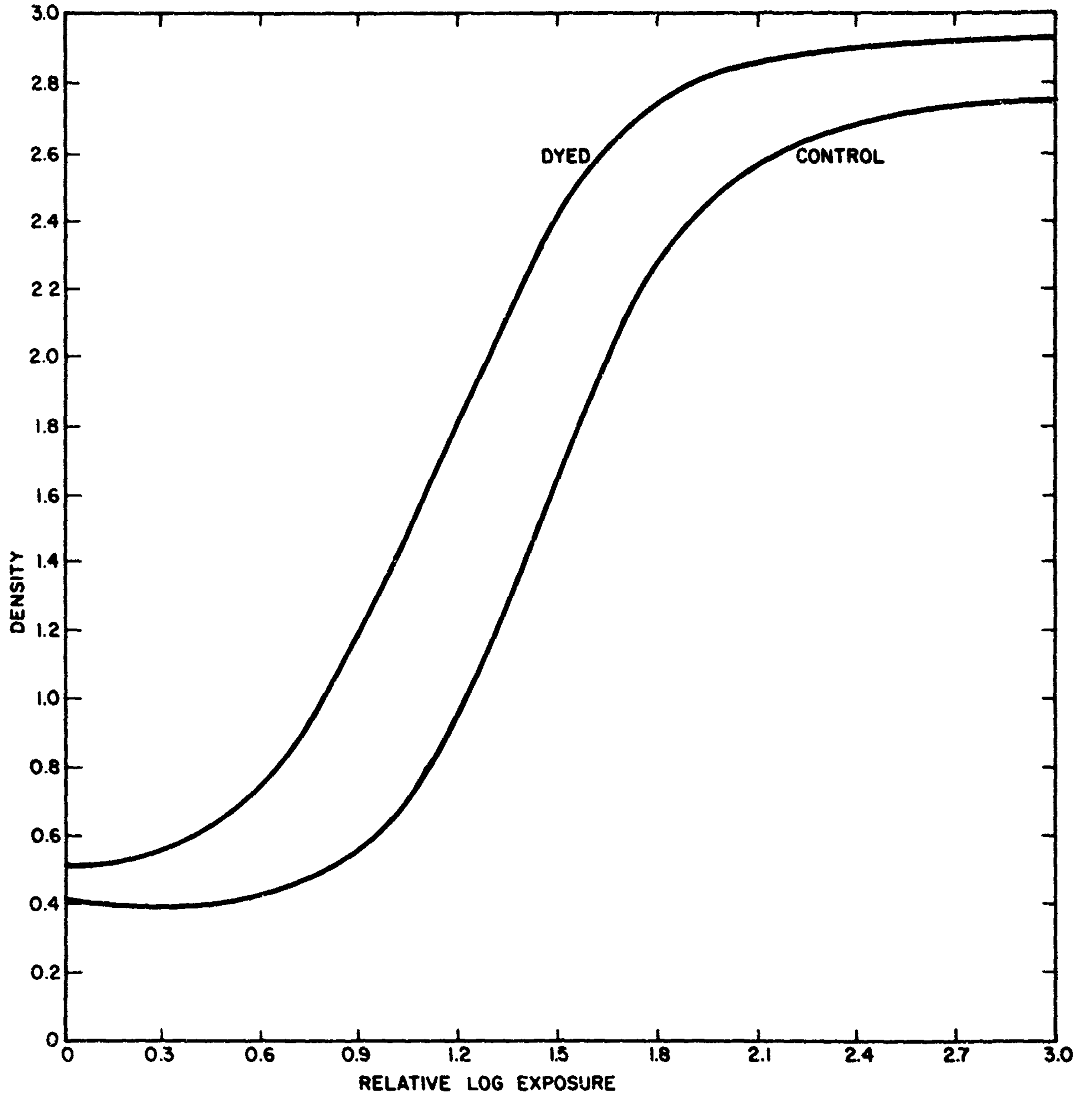

Figure 10. Increase of Green Sensitivity on Sensitization of Infrared Film with Erythrosin (520 nm filter)

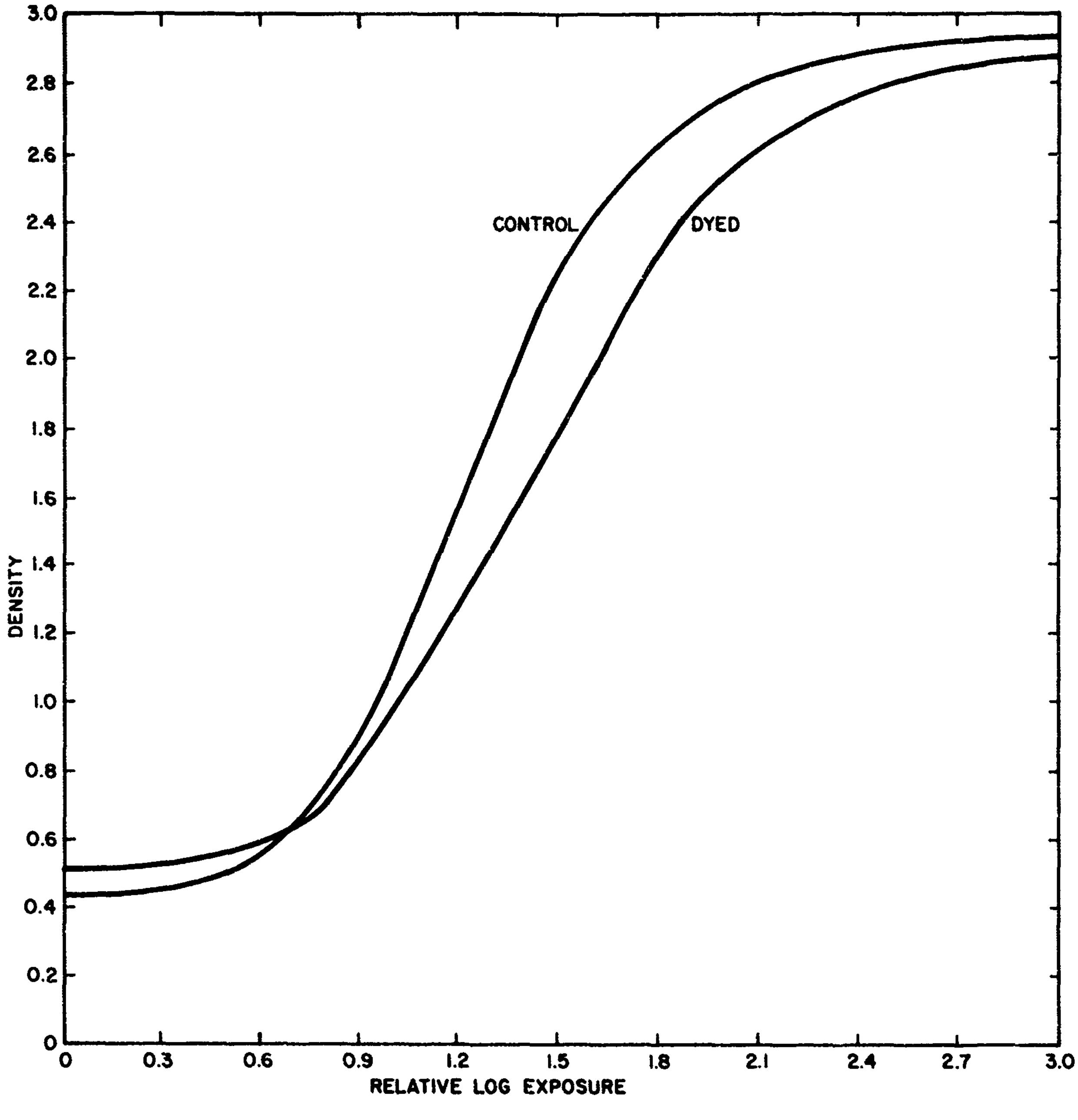

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Figure 11. Influence of Green Sensitization on Infrared Sensitivity of High Speed Infrared Film (Wratten 87 filter)

When the new Kodak High Speed Infrared film 2481 was received, similar tests were run, but the film only picked up a slight magenta cast in isolated spots. The staining effect noted with the unhardened 5218 emulsion was not observed, and there was no separation between H and D curves for control and dye-immersed strips sensitometrically exposed at 520 nm. Apparently the hardening of the new emulsions affects their permeability and prevents access of the dye to the silver halide grains.

EVALUATION OF CHARACTERISTICS OF NEW INFRARED FILMS

Selection of Infrared Modulating Dye

On Contract F33615-69-C-1084 we attempted to use Neocyanine as an infrared modulating dye, but it was not soluble enough to provide good density. Indocyanine Green (disodium salt of 3, 3, 3′, 3′-tetramethyl-1, 1′-di(4-sulfobutyl)-4, 5, 4′, 5′-dibenzoindotricarbocyanine iodide[6]), a more soluble infrared absorber, was obtained at the end of that program, too late for us to do any evaluation work. To see whether this dye was an improvement over Neocyanine, we prepared equal volumes of saturated dye solutions in alcohol containing 5 percent of PVP/VA E-635 (a vinylpyrrolidone-vinyl acetate copolymer available from GAF) and dropped aliquots of filtered solution onto rapidly spinning 2 in. x 2 in. glass plates. Half of the dye film was wiped from each plate and each, in turn, was inserted into the filter slot in a modified TOC camera. Kodak Infrared Aerographic film 2424 was exposed in the TOC camera to the flat field of light provided by the output of a tungsten lamp passing through a diffusing screen. The lens aperture of the camera was set at f/22 and exposures were made over the range of 1/500 sec to 1/8 sec. The film was tightly in contact with the partially dyed plates during exposure, and each exposure sequence was repeated with Wratten 87 and 89B filters, respectively, in the light path. The film strips were processed for 8 min in D-19, fixed, and dried.

Densitometer readings were made on the unattenuated and dye-attenuated halves of each strip and H and D curves were plotted. Since the curves were similar for each of the Wratten filters used, we show only the results for the 89B filter in Figures 12 and 13. The data of these Figures indicate that Indocyanine Green absorbs considerably more infrared energy than Neocyanine.

Determination of Optimum Carrier Frequency

Since the carrier frequency ultimately determines the system resolution, we wished to operate at as high a frequency as feasible. Therefore the response of the new films was checked in several ways with 40 ℓ/mm and 33 ℓ/mm carriers.

Comparison of Ronchi Rulings. First 2424 film was exposed in a "black box" camera, a device fabricated at Tech/Ops specifically for making multiple exposures on a single film frame. The camera has, at its exposure plane, a grating holder that can be rotated to 0, 45, and 90 degrees, with detents for locking it in these

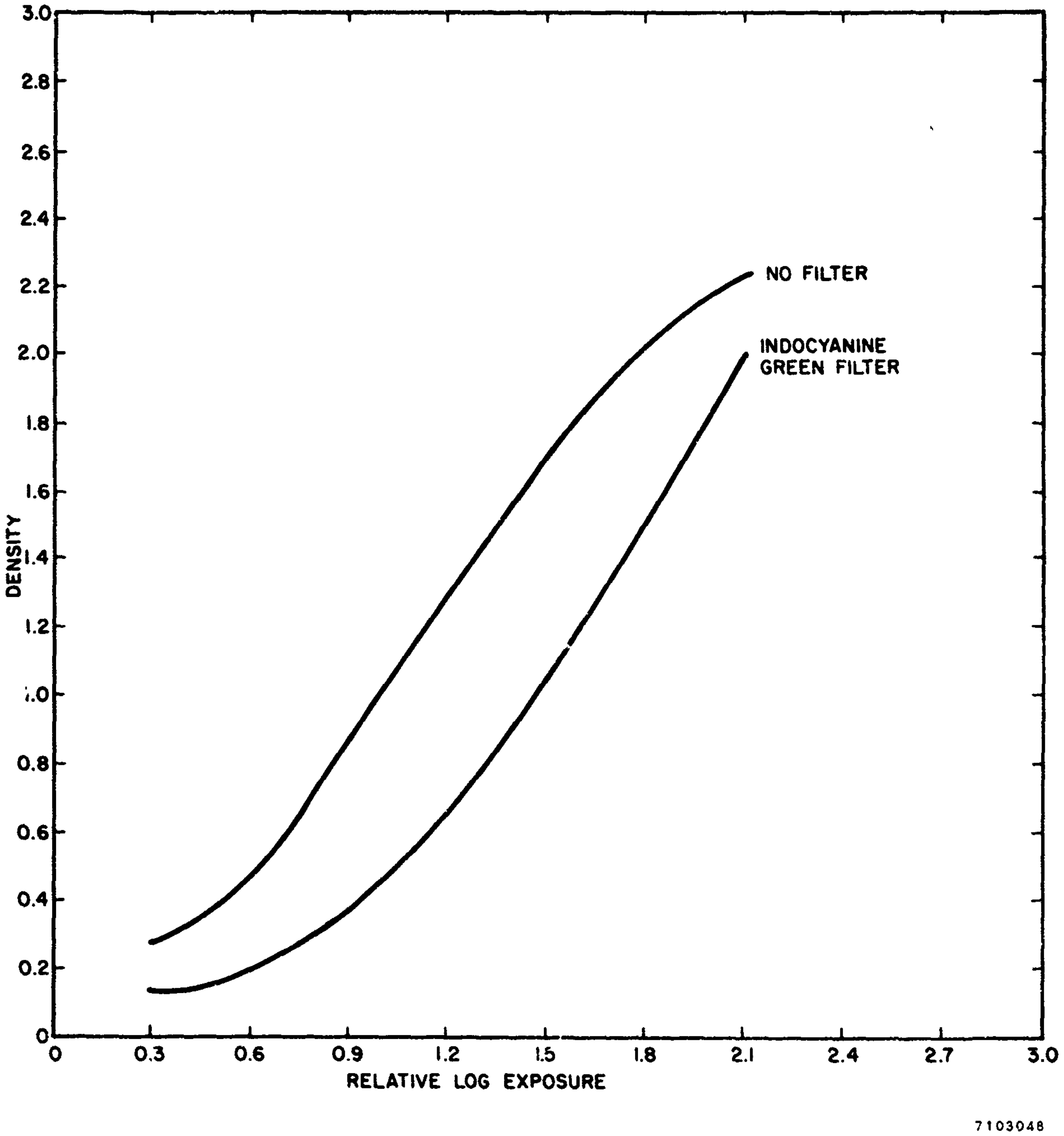

Figure 12. Effect of Infrared Absorption by Indocyanine Green on Response of 2424 Film to Light Passing a Wratten 89B Filter

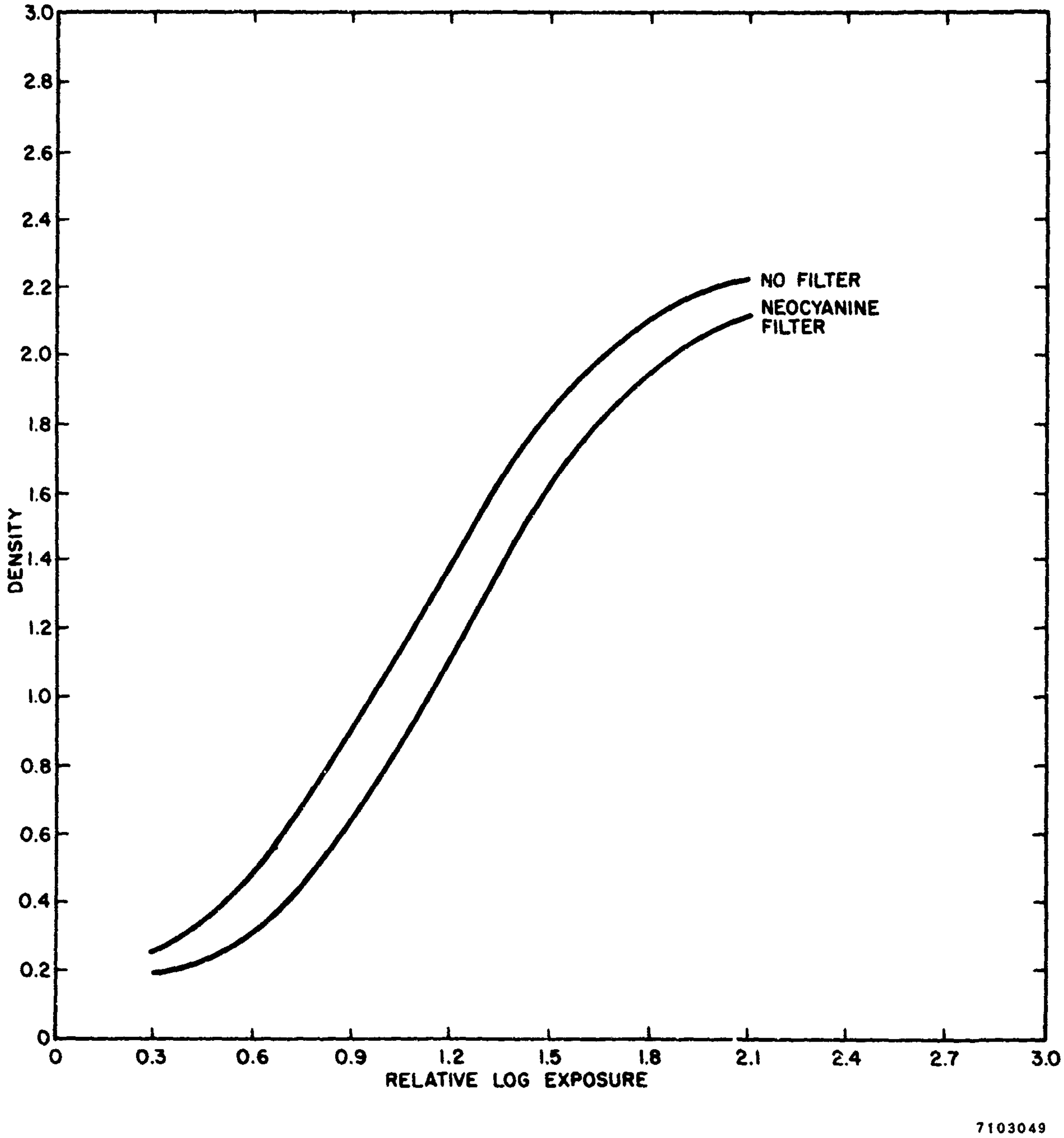

Figure 13. Effect of Infrared Absorption by Neocyanine on Response of 2424 Film to Light Passing a Wratten 89B Filter

positions. A releasable pressure platen holds the film in contact with the grating during exposure. For this test a 40 ℓ/mm Ronchi ruling was inserted in the camera, and exposures were made to a flat field of light as described previously with first a Wratten 87, then the red, and finally the green separation filter of Figure 5 in the light path. The sequence was repeated with a 33 ℓ/mm Ronchi ruling in the camera. The films were developed for 8 min in D-19, fixed, and dried. From the microdensitometer traces made across the line patterns we obtained the ΔD values shown in Table I.

Table I. Relative Diffraction Potential of Line Patterns on 2424

Filter	Relative Log E	ΔD at Frequency	
		40 ℓ/mm	33 ℓ/mm
Infrared	0.0	0.182	0.238
	.3	.392	.588
	.45	.546	.812
	1.00	.546	.924
	1.10	.294	.812
Red	2.0	.224	.392
	2.3	.546	.672
	2.45	.602	.994
	2.75	.406	.800
	2.90	.308	.798
Green	2.3	.182	.266
	2.6	.364	.588
	2.9	.490	.870
	3.2	.462	.840
	3.5	.322	.364

The data of Table I indicate that the peak ΔD values at 33 ℓ/mm are at least 60 percent higher than those at 40 ℓ/mm. In addition, the peak regions are broader at the lower frequency. Confirmatory tests were made by sequential exposures of the

special transparent target described in the previous final report (Ref. 4, p. 29). To record all the target patches successfully at 40 ℓ/mm, the infrared exposure had to be controlled within one third of a stop, the red exposure had to be kept within one stop, and the green exposure within half a stop. At 33 ℓ/mm the infrared and green exposures could be varied by a stop and a half, whereas the red exposure could be varied by two stops. The increased latitude at the lower carrier frequency confirms that the film resolution is better adapted to recording at 33 ℓ/mm and suggests that an even lower frequency might be desirable.

Modulation Efficiency of Indocyanine Green. As a final check, we wished to determine the effect of substituting an Indocyanine Green grating for the Ronchi ruling. First, 40 ℓ/mm and 33 ℓ/mm patterns were exposed into photoresist coated on 2 in. x 2 in. glass plates. The grooves resulting from the washing away of unhardened photoresist were filled with Indocyanine Green in the PVP/VA E-635 vehicle. The gratings thus formed were placed in the grating holder in the black box camera, and a sequence of exposures was made through a Wratten 87 filter. The line patterns on the processed films were analyzed by microdensitometry to determine ΔD and by diffractometry to determine diffraction efficiency. The data obtained for the 33 ℓ/mm rulings are summarized in Figures 14 and 15. Similar results, but with lower peak heights, were obtained at 40 ℓ/mm. The Indocyanine Green grating appears to be almost as effective as the Ronchi ruling for modulating infrared energy.

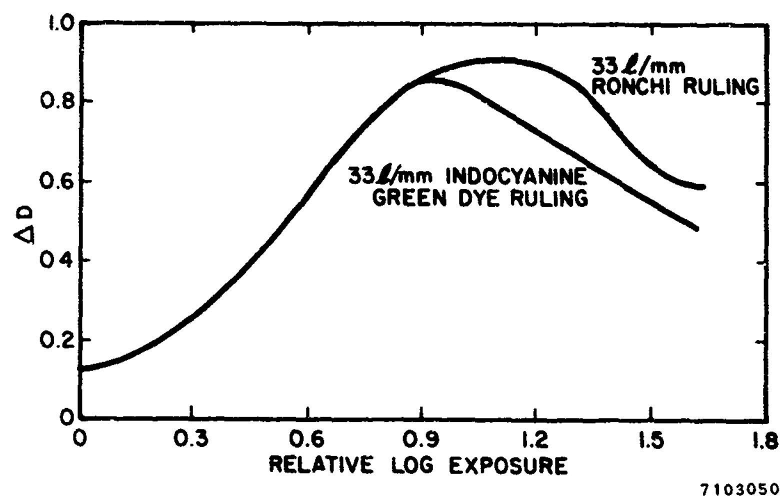

Figure 14. Infrared Modulation Potential of Indocyanine Green Grating Compared to Ronchi Ruling (infrared film 2424 exposed through Wratten 87 filter)

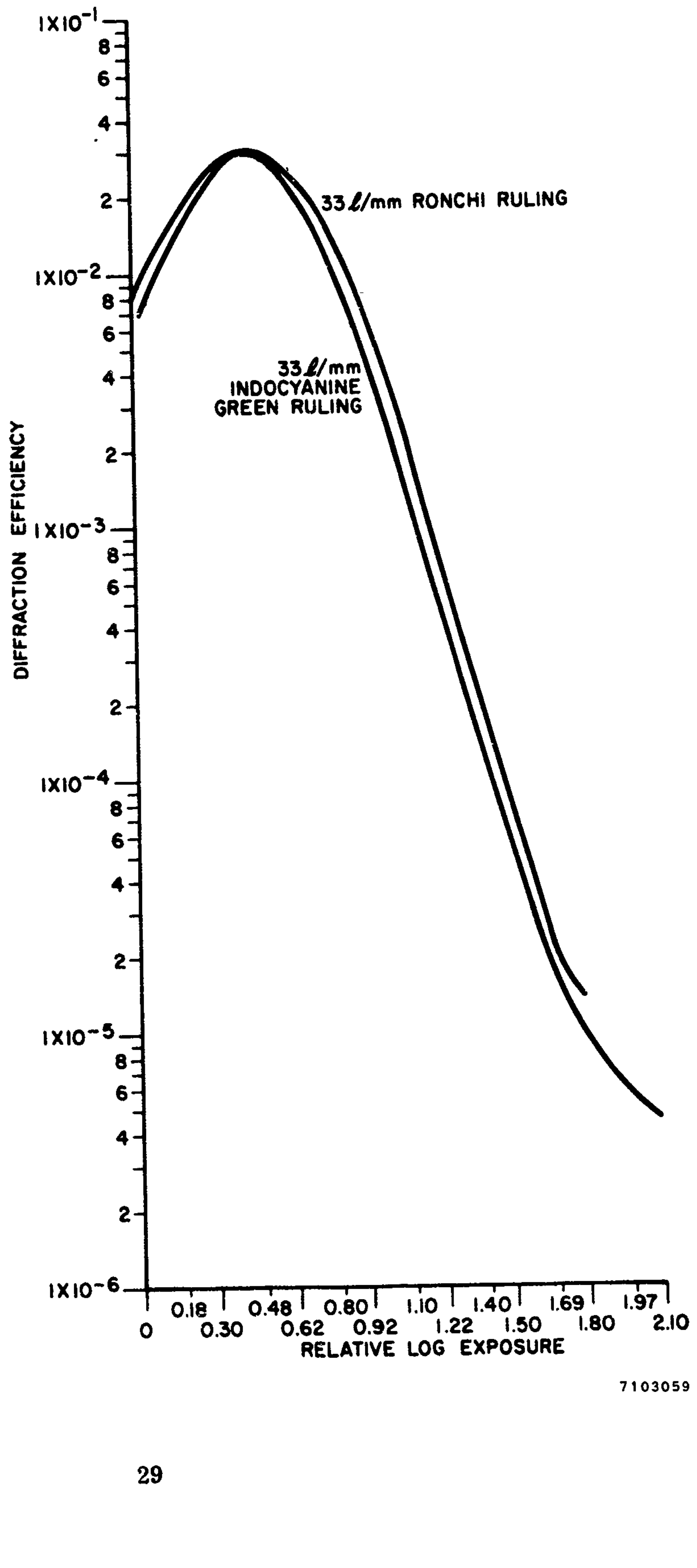

Figure 15. Diffraction Efficiency of Indocyanine Green Grating Compared to Ronchi Ruling (infrared film 2424 exposed through Wratten 87 filter)

Film Sensitivity Comparisons

The black box camera exposures indicated that the latitude of the infrared film was not sufficient to handle the imbalance in sensitivity between its green, red, and infrared response. However, since we were using an uncorrected tungsten light source, the output of which is heavily overbalanced in red and infrared, a sequence of outdoor exposures was made to the standard color target used for evaluating panchromatic films. This target, shown schematically in Figure 16, had patches of the three primary colors -- red, green, and blue -- with patches of the corresponding subtractive colors -- cyan, magenta, and yellow -- directly underneath. Naturally, the colors of the patches do not record properly on infrared film because the infrared reflectivity of each patch influences the "color" seen by the film. However, by photographing the target first through a Wratten 12 filter and then through a Wratten 89B filter, we hoped to estimate the contribution of the red and green exposures to the total density of each patch. The film sensitivity was high enough that a 1.5 neutral density filter had to be used in front of the camera lens to keep exposure times within a reasonable range. The data obtained for the primary colors only are summarized in Table II.

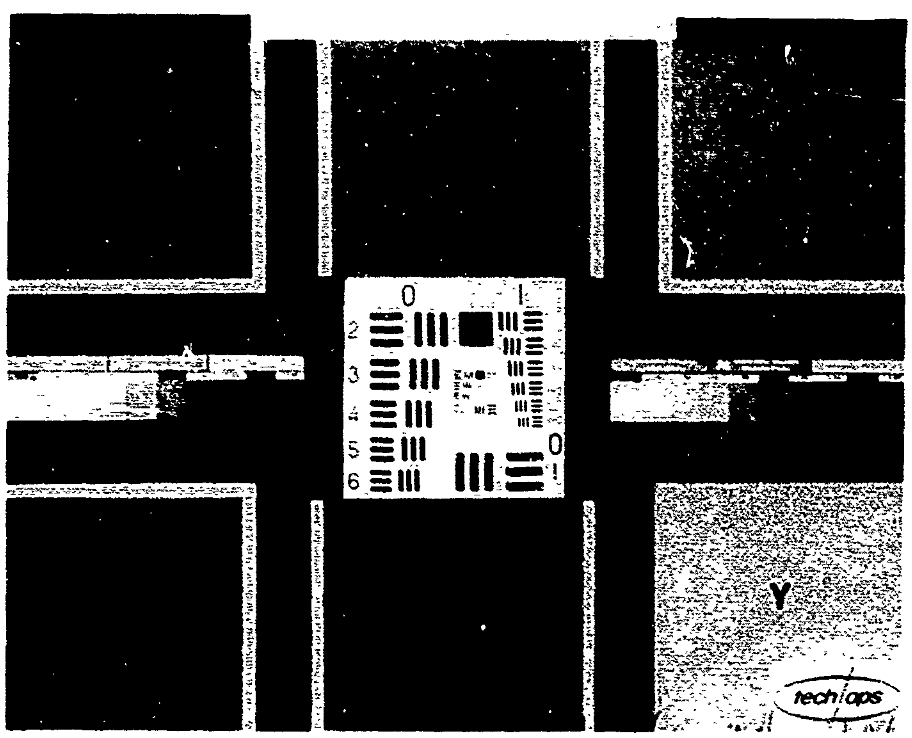

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Figure 16. Six Color Patch Target

Table II. Comparison of Overall Sensitivity of 2424 Film to Its Infrared Sensitivity

Exposure (sec at f/8)	Density of Green Patch		Density of Red Patch		Density of Blue Patch	
	Wratten 12	Wratten 89B	Wratten 12	Wratten 89B	Wratten 12	Wratten 89B
1/1000	0.15	0.14	0.30	0.27	0.25	0.24
1/500	.17	.17	.49	.44	.39	.36
1/200	.29	.26	.77	.69	.63	.60
1/125	.48	.42	1.18	1.10	.98	.97
1/60	.75	.71	1.56	1.51	1.40	1.40
1/30	1.15	1.14	1.91	1.88	1.82	1.82

The result from the blue patch of the target, which should reflect only infrared (blue is filtered out in both exposure sequences), is included in Table II to illustrate the likely experimental variation. The comparisons for the green and red patches indicate that the infrared response of the film is so overpowering that the density contribution from its visible light sensitivity barely exceeds the density fluctuation produced by experimental error. It is apparent from this result that the film cannot be used as it is with a tricolor grating; modulated imagery would be recorded only in the infrared coding direction.

Individual Color Response. To gain an estimate of the type of color correction needed before the film could be used as a basis for a tricolor system we photographed the color target outdoors through the individual color separation filters shown in Figure 4. A comparison of the relative densities observed for the green and red color patches is shown in Table III.

The data of Table III confirm that the red reflectivity of the green patch and the green reflectivity of the red patch are minimal, as we would expect. The infrared reflectivity of the green patch is considerably lower than the infrared reflectivity of the red patch. Thus, the two stop exposure difference needed to balance the green densities obtained through the green and infrared separation filters can be taken as a measure of the minimum difference in sensitivity between the two color bands of the film. Actually, the yellow patch of the color target, when photographed on Ektachrome Infrared Aero film, appears to be neutral. This indicates that its green, red, and infrared reflectivities are matched as far as the characteristics of the Ektachrome are concerned. A comparison of the density values for the yellow patch obtained through the separation filters is shown in Table IV. These data

Table III. Color Separations on Color Patch Target

Exposure (sec at f/8)	Density of Green Patch Through Filter			Density of Red Patch Through Filter		
	Green	Red	Infrared	Green	Red	Infrared
1/60	0.29	0.13	0.81	0.15	0.69	1.60
1/30	.53	.16	1.27	.18	1.06	1.93
1/15	.78	.22	1.61	.26	1.42	2.09
1/8	1.31	.46		.55	1.88	
1/4	1.65	.71		.74	2.07	
1/2	1.92	1.04		1.16	2.19	

Table IV. Comparative Densities of Yellow Color Patch

Exposure (sec at f/8)	Density of Yellow Patch Through Filter		
	Green	Red	Infrared
1/60	0.38	0.62	1.48
1/30	.66	1.07	1.88
1/15	.94	1.45	2.08
1/8	1.49	1.85	
1/4	1.79	2.06	
1/2	2.00	2.17	

indicate a consistent difference of two stops between red and infrared sensitivity and three stops between green and infrared sensitivity.

Sensitometric Estimation of Color Sensitivity Difference. The same exposures that generated the color separation data also generated sensitometric data from reflectance gray wedges included as part of the color target format. Low resolution microdensitometer traces across the wedge images gave the data plotted in Figure 17. The separation between the curves again indicates a difference of two to three stops in sensitivity between the infrared and the two visible color bands. This difference cannot be regarded as quantitative since the reflectivity of the gray wedge probably is not quite the same in the infrared as it is in the visible.

Attempted Correction of Film Sensitivity Balance

To determine whether the sensitivity bands of Kodak Infrared Aerographic film 2424 could be brought into balance without undue loss of film speed, tricolor encoding gratings had to be prepared. These 33 ℓ/mm gratings had a set of cyan lines (provided by the dye Irgacet Brilliant Blue), a set of magenta lines (provided by the dye Sulforhodamine B) perpendicular to the cyan set, and a set of Indocyanine Green lines at 45 degrees to the other two sets. When they were placed in a TOC camera and exposures were made onto infrared film, the only lines observed at any exposure level were in the infrared coding direction. Corning 1-57 and 1-56 infrared cutting filters were next used in front of the camera to filter out some of the impinging infrared energy. With the lighter of the two filters (1-57), the red playback color (infrared channel) still predominated to the exclusion of the others. With the 1-56 filter, sufficient infrared energy was subtracted to render the red false color playback weak.

A second generation of tricolor gratings was prepared. The magenta dye concentration was increased to improve green modulation, and a thin film of Indocyanine Green was put over the face of the grating to serve as the integral infrared filter. These gratings, when used with the 1-57 filter, gave rise to imagery showing all three line directions. The colors observed on reconstruction from this imagery were lacking in saturation, and the film had to be exposed at an approximate ASA level of 1.

Comparison Exposures on Ektachrome Infrared Aero Film

To aid in evaluating both color and speed data on the black-and-white infrared films, we made comparison exposures on Ektachrome Infrared Aero film 8443.

Color Target Evaluation. The color target used for the early work was designed for use with standard panchromatic films. To determine the false color response to be expected from a tricolor infrared film, the target was photographed outdoors

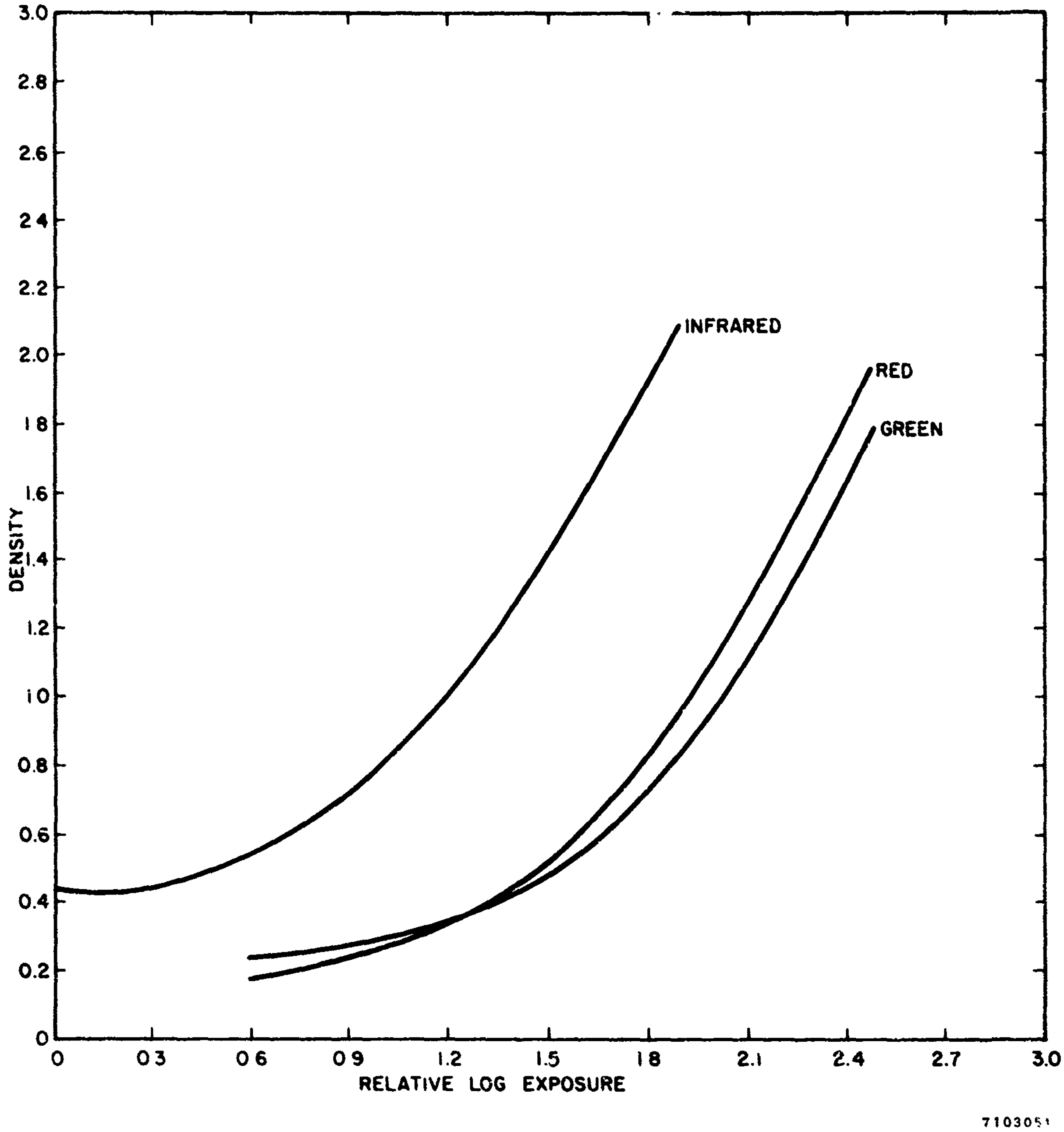

Figure 17. H and D Curves from Reflectance Wedges Photographed Through Color Separation Filters

through an exposure range of 1/500 sec to 1/30 sec (f/9.5). The Ektachrome film was processed in Kodak E-3 chemistry, and densities were determined for each color patch through the standard red, green, and blue filters in the MacBeth QuantaLog® densitometer. The response curves for the individual patches are shown in Figures 18 through 23. The red color patch of the target reflects red and infrared almost equally, b ts green reflectance is negligible. In false color configuration the playback for t..is patch would show equal amounts of red and green, and the patch would appear yellow to the eye. The green color patch of the target reflects green, and its infrared and red reflectances are negligible. In false color configuration this patch would appear blue. The blue color patch of the target reflects infrared, and its red and green reflectances are negligible; thus it should appear to be red. Of the subtractive colors, the yellow reflects almost equivalent amounts of red, green, and infrared and appears white. Actually, since its infrared reflectivity is slightly lower than its visible reflectivity, it may take on a slight cyan cast at higher exposures. The magenta patch is similar to the red patch in that it has reasonably balanced red and infrared reflectivities and a negligible green reflectivity. It, therefore, should exhibit a similar yellow appearance in false color configuration. The cyan patch is the least reflective of all the patches and will always appear to be darker than the others. It reflects green and infrared best at high levels of illumination. These reflectances correspond to blue and red false colors, and the patch appears magenta. At lower light levels, the reflectivities of the three colors are fairly well equalized and the patch appears a neutral gray or black.

An additional fact is apparent from examination of the H and D curves for the color patches. The curves for the predominating colors are all very steep, which indicates that the film has poor latitude.

Evaluation of Speed and Balance of Individual Layers

When we consider any of the available black-and-white infrared films as a color receptor, we are dealing with the equivalent of a tripack color film with layers of widely different sensitivity. Since the sensitivity curves for Ektachrome Infrared Aero film provided by Kodak are expressed in terms of the exposure necessary to reduce the dye density to a given value, they do not tell us the actual sensitivity of the individual black-and-white layers making up the film. We, therefore, tried to determine relative values for each layer to assess the sensitivity balance.

The Tech/Ops Spectral Sensitometer is provided with a set of dichroic filters peaking at 60 nm intervals. The diameter of the aperture of each filter holder is regulated so that equal energy impinges on the exposure plane regardless of the filter chosen. The filter set has 520 and 640 nm filters but no infrared filter. An infrared dichroic filter peaking at 840 nm was available, and we matched it to an aperture that gave the same energy at the exposure plane as measured for the other two filters. (A Coherent Radiation Laboratories Power Meter 212 was used to measure the relative energies.) Sensitometric exposures were made at the three wavelengths, and the exposed films were processed for 8 min in D-19,

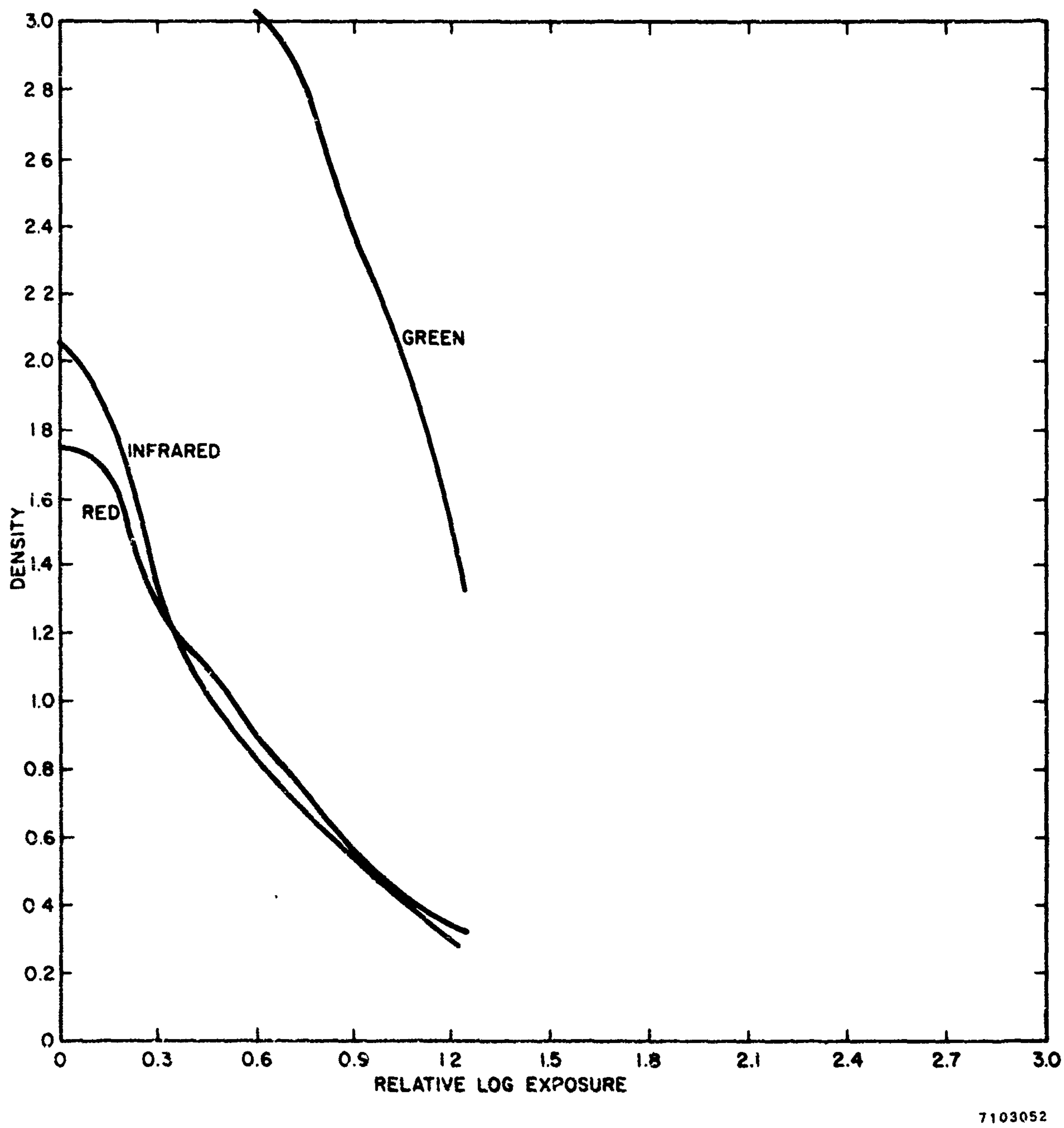

Figure 18. Response of Red Target Patch on Ektachrome Infrared Aero Film

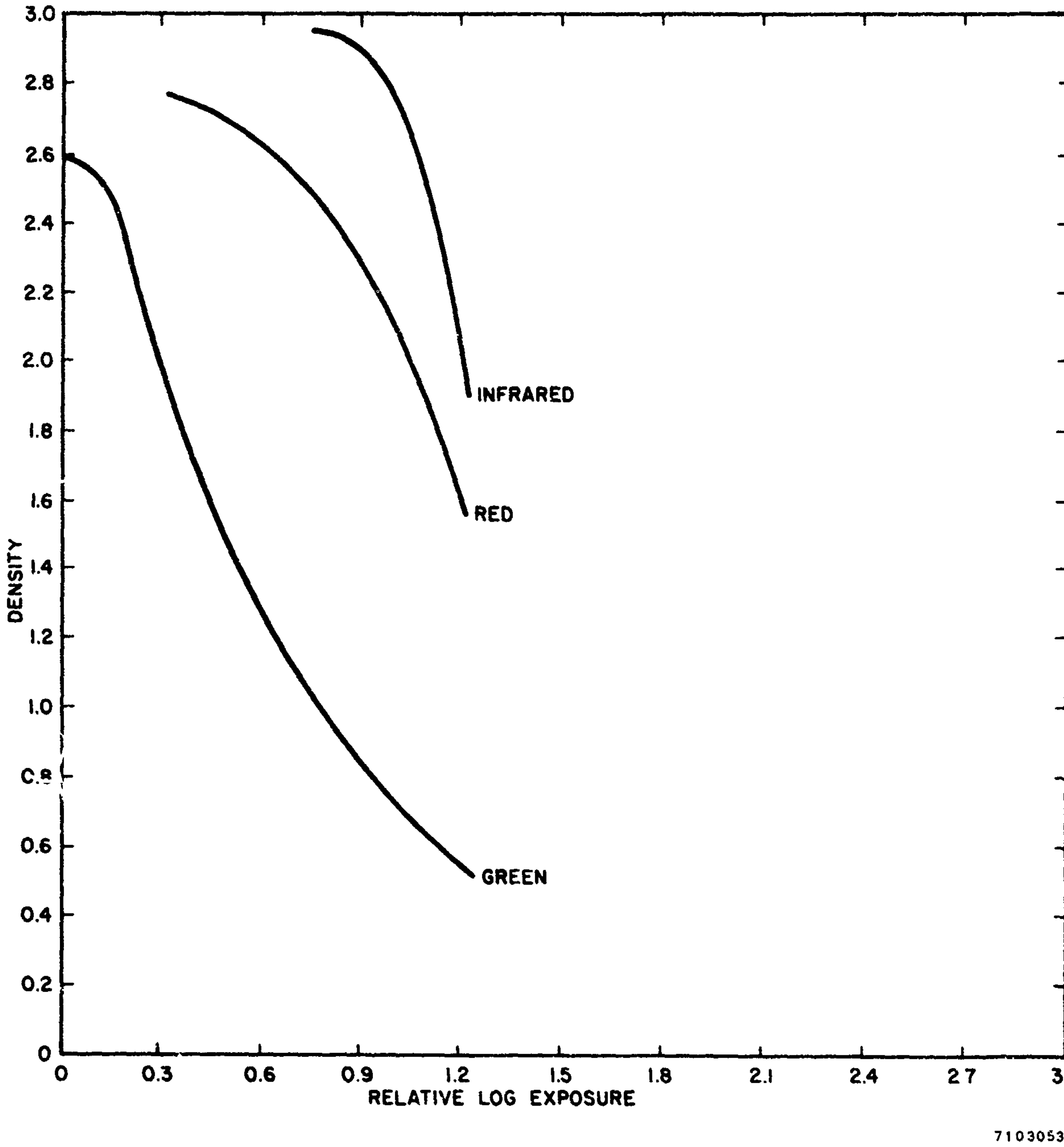

Figure 19. Response of Green Target Patch on Ektachrome Infrared Aero Film

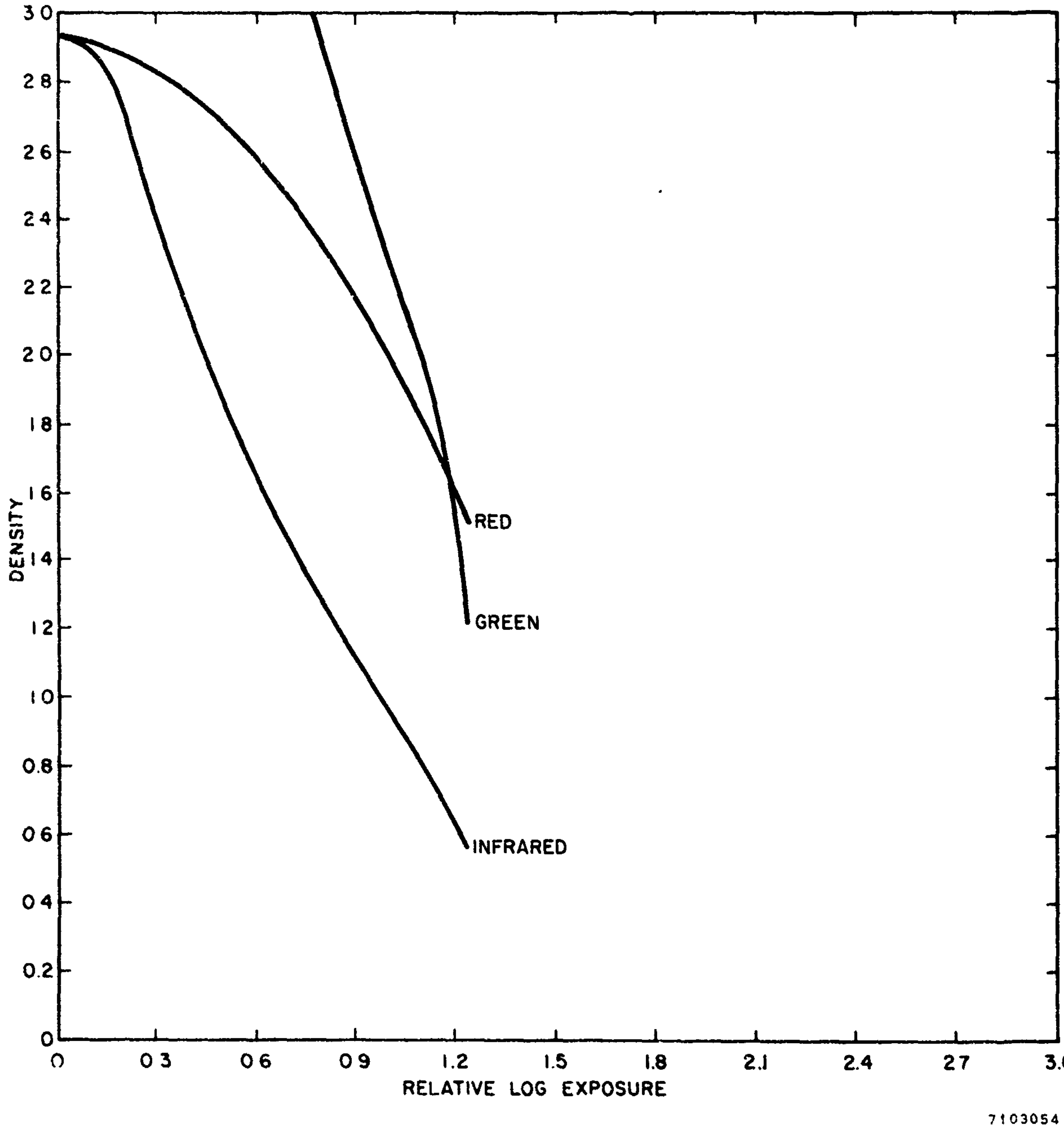

Figure 20. Response of Blue Target Patch on Ektachrome Infrared Aero Film

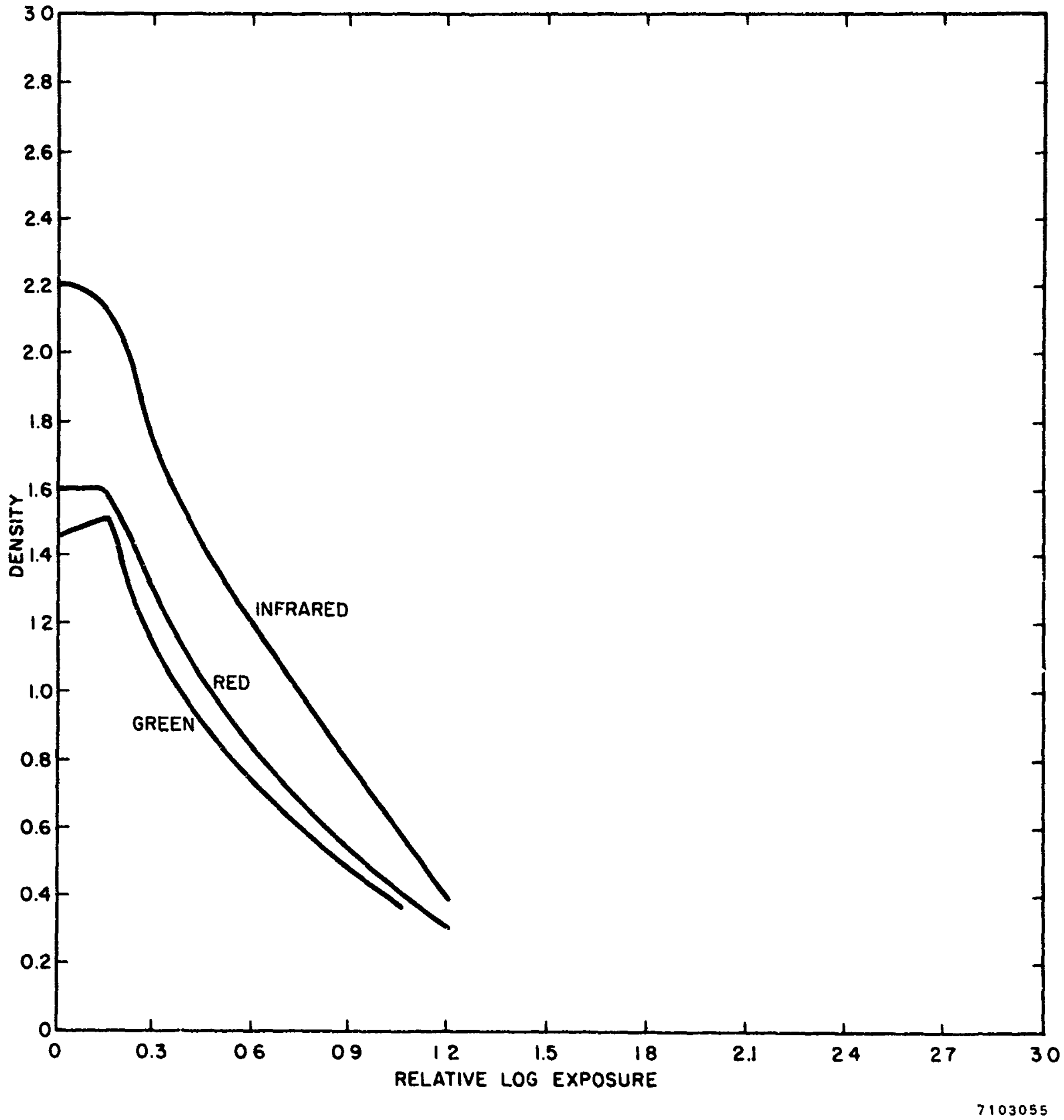

Figure 21. Response of Yellow Target Patch on Ektachrome Infrared Aero Film

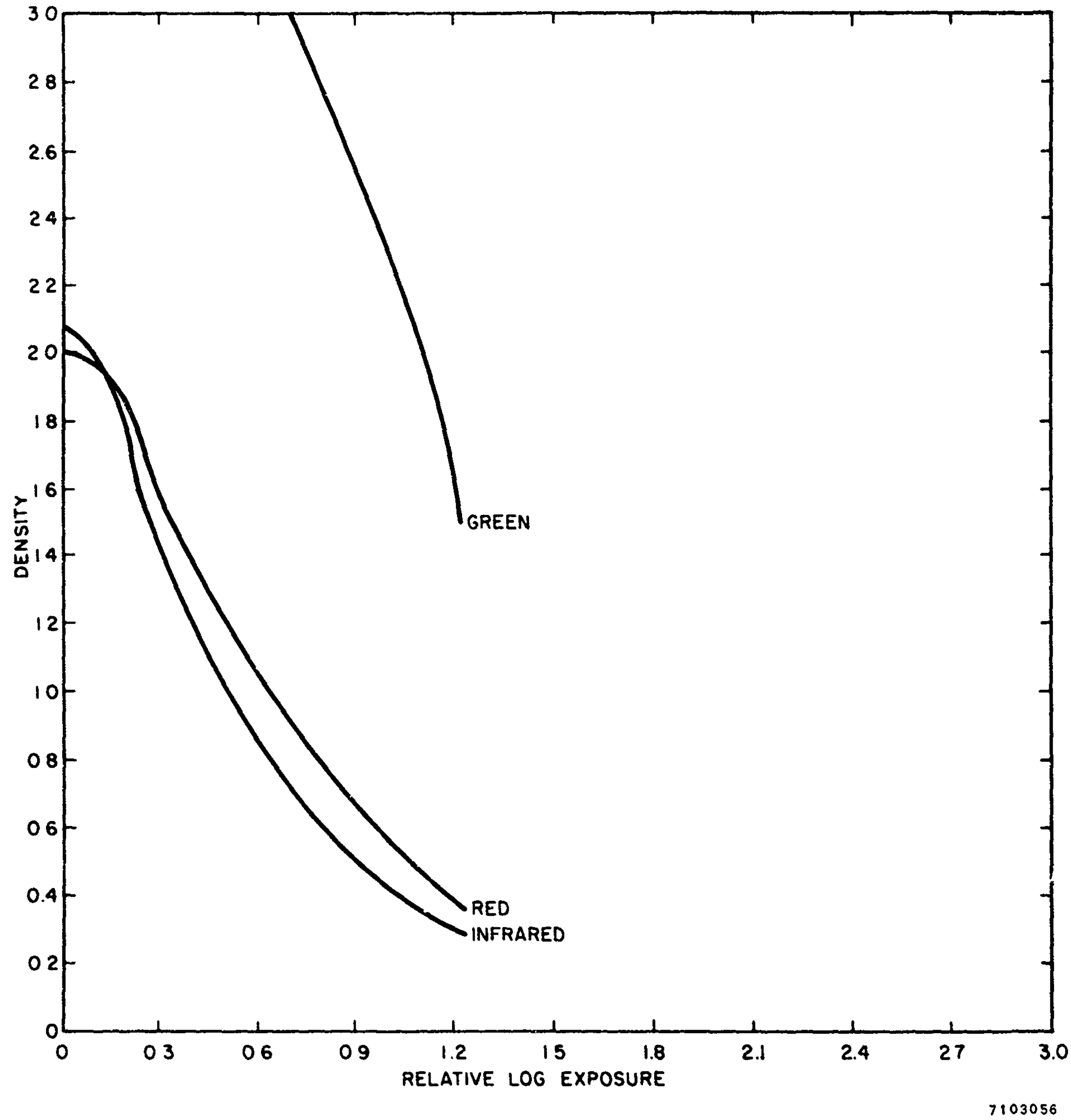

Figure 22. Response of Magenta Target Patch on Ektachrome Infrared Aero Film

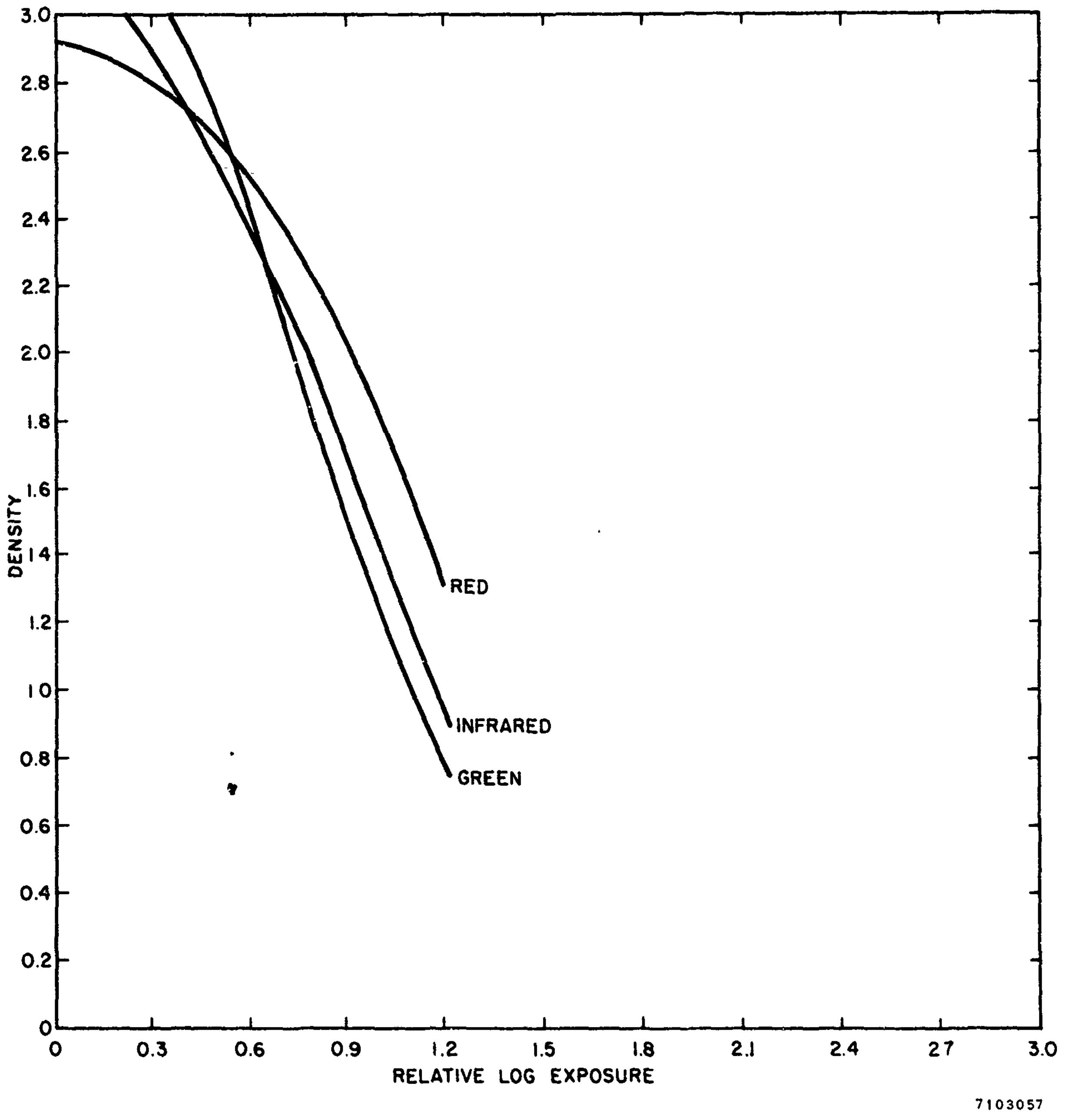

Figure 23. Response of Cyan Target Patch on Ektachrome Infrared Aero Film

fixed, and washed. A uniform-appearing dark greenish yellow background was present on all the sensitometric strips since, by not bleaching as in the regular color process, we did not destroy the filter layer. When densitometric measurements confirmed that the background was indeed uniform, we subtracted the fixed density from each step of the wedge and plotted the corrected densities to obtain the curves of Figure 24. The additional (broken line) curve is the result of a sensitometric exposure through the 520 nm filter onto Kodak Infrared Aerographic film 2424. Although the gammas for the three layers of the Ektachrome are different (no doubt compensated for in the color coupling), the toe speeds are very close, and we can regard the layers as being of equivalent sensitivity.

The position of the H and D curve for the green exposure on 2424 indicates that the speed of the minimum sensitivity band of the black-and-white emulsion is lower than the speed of any of the emulsion layers of the color film. Since the H and D curve for the red exposure (640 nm filter) on 2424 falls almost on top of the curve for the green layer of the Ektachrome, it was omitted to avoid confusion. Thus the individual emulsions that make up the Ektachrome apparently are sensitized to a level represented by the red sensitivity of 2424.

Effectiveness of Tricolor Gratings. We also used the Ektachrome Infrared Aero film to test the effectiveness of the first generation tricolor gratings. The film was exposed in a TOC camera in contact with the grating. The color patch target was again used as the subject. The film was processed to a positive transparency using a black-and-white reversal process, the essential steps of which are listed below.

Kodak D-94	3.5 min
Kodak R-9	2 min
Kodak CB-2	1 min
Expose 10 sec to photoflood	
Kodak D-95	1 min
Kodak Rapid Fix	2 min

The transparencies were examined under the microscope, and line structure was evident in all three directions. In addition they were viewed in a TOC reconstructor and two of the primary colors appeared to be strong and one appeared weak. Thus the Ektachrome provides a good method for screening new tricolor gratings.

ALTERNATIVE FALSE COLOR SYSTEM

The early experimental work of the contract clearly showed that the sensitivity imbalance of present black-and-white infrared films was too severe for correction by simple filtration techniques. Color systems having an infrared band must necessarily be "false color" systems because the color recorded on the film bears no

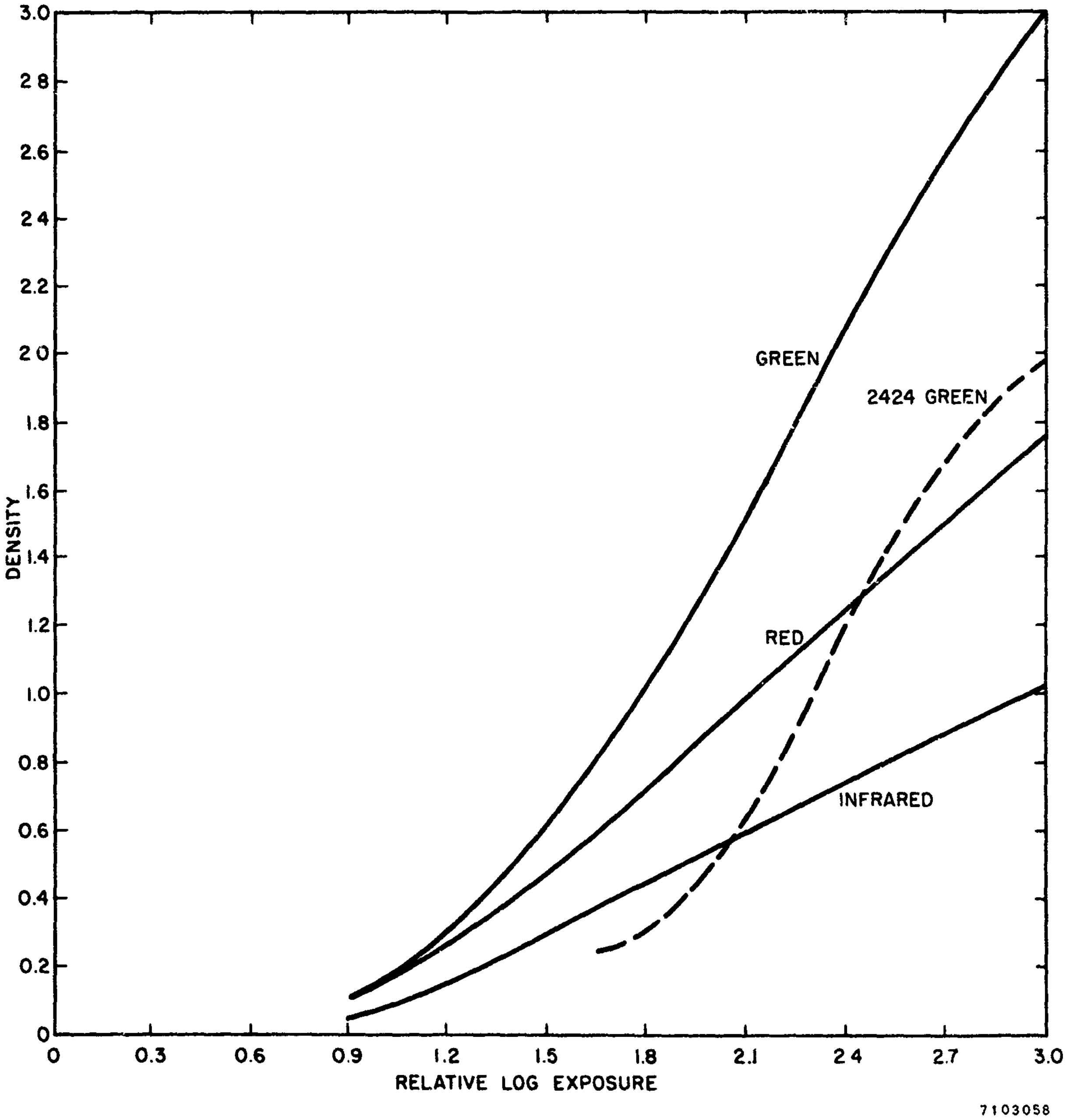

Figure 24. Comparative Sensitivity of Emulsion Layers in Ektachrome Infrared Aero Film

simple relation to the color seen by the eye at the time of recording. This being the case, we might gain just as much information by selecting three random spectral bands of equal sensitivity, matching subtractive dyes to these bands, and assigning one of the three primary colors as the false color representation of each band in the reconstruction system. The first step in setting up a random false color receptor based on a black-and-white infrared film was to gain information useful to the selection of the arbitrary color bands.

Film Sensitivity Distribution

To divide the film response into equal segments we had to determine the sensitivity distribution by integrating the published sensitivity curve for 2424 infrared film. The values were normalized at 420 nm, the point of maximum sensitivity, and the sensitivity was summed for the nominal color regions: 400 to 500 nm for blue, 500 to 600 nm for green, 600 to 700 nm for red, and 700 to 900 nm for infrared. Table V lists the values obtained.

Table V. Relative Sensitivity Values for Kodak Infrared Aerographic Film 2424

$$\sum_{400}^{500} = 6.4428 \qquad \sum_{400}^{900} = 13.8053$$

$$\sum_{500}^{600} = 0.6523 \qquad \sum_{500}^{900} = 7.3725$$

$$\sum_{600}^{700} = 1.5825 \qquad \sum_{700}^{800} = 2.5047$$

$$\sum_{700}^{900} = 5.1277 \qquad \sum_{800}^{900} = 2.6230$$

It is quickly apparent that there are only two possible ways to arrive at three bands of roughly equal sensitivity. One is to divide the infrared region into two equal parts; the other is to utilize a portion of the vast sensitivity reservoir in the blue spectral region that is normally filtered out during exposure. The former approach appeared to offer the simplest solution. The infrared region can be divided into two equal bands, 700 to 800 nm and 800 to 900 nm, which have matched sensitivities. If the green and red bands are combined, the relative areas for the three bands become

$$\sum_{500}^{700} = 2.2348; \quad \sum_{700}^{800} = 2.5047; \quad \sum_{800}^{900} = 2.6230 \ .$$

These are matched closely enough to represent 30.4, 34.0, and 35.6 percent, respectively, of the total sensitivity. The maximum imbalance is approximately one quarter of a stop and could be reduced to the vanishing point by broadening the visible band slightly to 480 nm.

To verify that the published sensitivity curve was accurate, we made equal energy exposures onto 2424 film through the series of narrow band dichroic filters in the Tech/Ops Spectral Sensitometer. The H and D curves obtained (shown in Figure 25) indicate that the sensitivity increases in the order: green, red, infrared, blue. They also show the sensitivity minimum in the region of 520 nm and locate the sensitivity maximum close to 400 nm.

Grating Fabrications

The main problem facing this alternative color band system was the necessity for having two relatively narrow-band infrared absorbing dyes. The selection of infrared dyes on the market is poor, and Indocyanine Green was the only available dye having anywhere near the desired characteristics for our original infrared band. Fortunately, the spectrum of Indocyanine Green (see Figure 26) is relatively narrow, and it exhibits a sharp peak at 800 nm. Also, from previous contracts dealing with narrow-band sensitization, we had some spectral sensitizing dyes peaking fairly sharply near 750 nm. One of these, 1,1′,3,3,3′,3′-hexamethylindotricarbocyanine iodide (also shown in Figure 26), cut sharply at 800 nm and appeared ideal for our purposes.

Bicolor Gratings. To check the two alternative band selections we went through an intermediate stage of making 33 ℓ/mm bicolor gratings. The split infrared band was represented by a grating with the two dyes discussed above each occupying one of the line patterns. A Wratten 89B filter restricted the composition of the light passing through this filter to wavelengths absorbed by one or the other of the infrared dyes. The possible use of a blue spectral band was tested with a bicolor grating having an Indocyanine Green line pattern (infrared modulation) and a Spirit Yellow line pattern

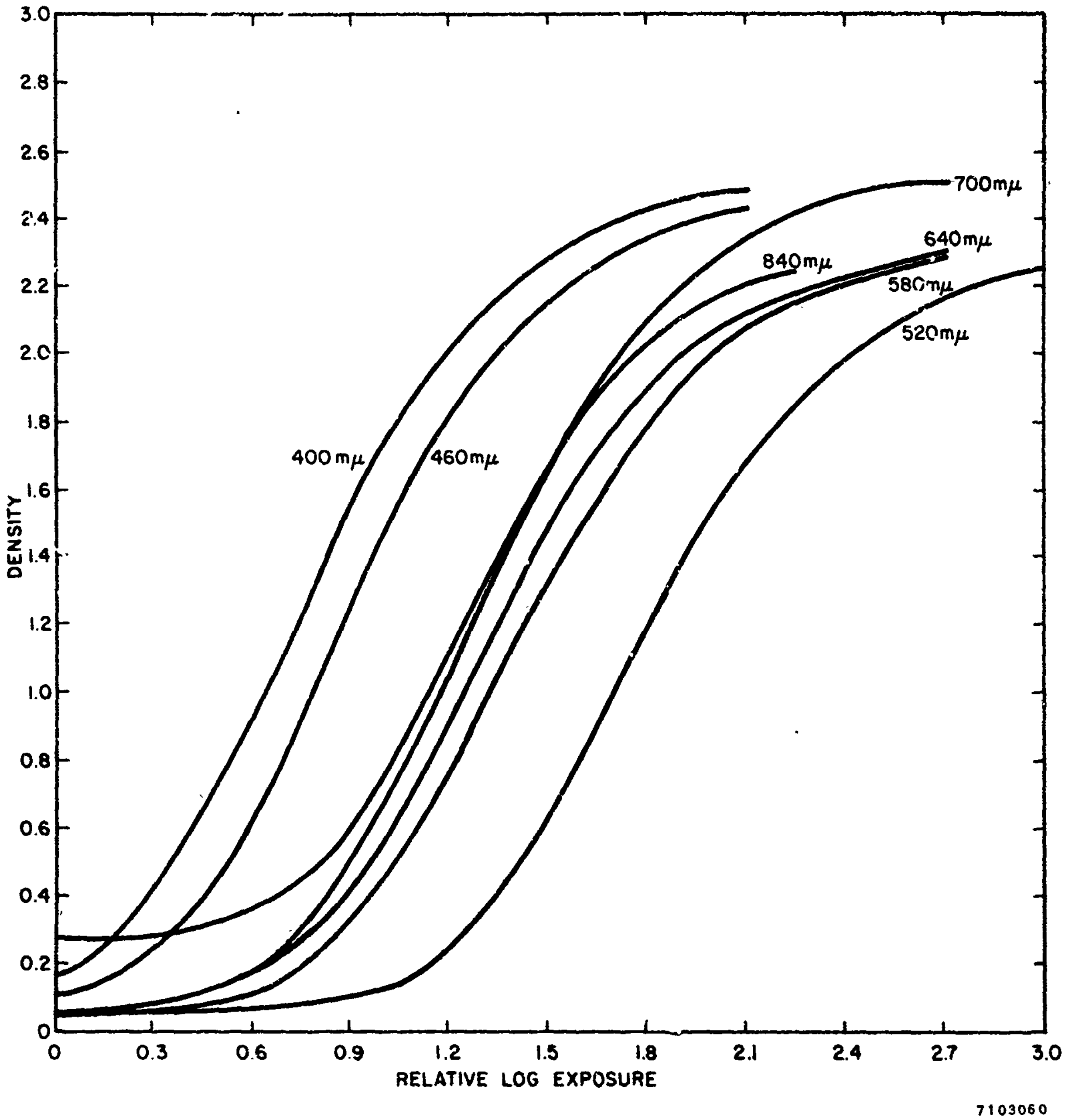

Figure 25. H and D Curves of Equal Energy Exposures Through Narrow-Band Filters of Various Wavelengths

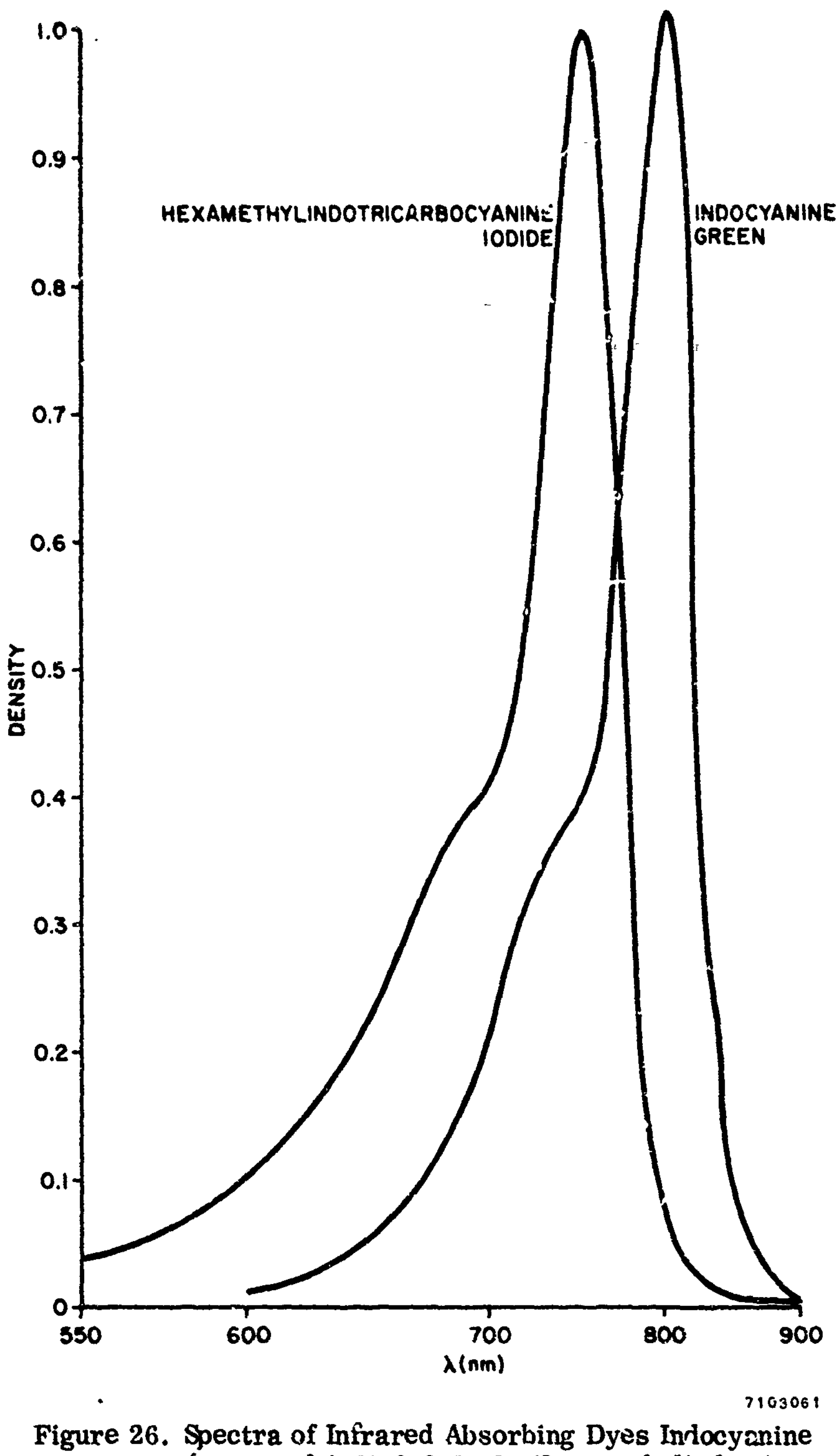

Figure 26. Spectra of Infrared Absorbing Dyes Indocyanine Green and 1, 1', 3, 3, 3', 3'-Hexamethylindotricarbocyanine Iodide

(blue modulation). Since we knew from earlier work that the density contribution from red and green light was negligible at exposures proper for recording infrared energy reflected from our standard color target, we did not attempt to filter out red or green light when testing this filter.

To test the discrimination of the split infrared band bicolor filter, a special transparency target was prepared. It consisted of seven filter patches: the Wratten 87, 87C, 88A, and 89B filters and three special filters prepared at Tech/Ops. Two of the filters were prepared by dipping subcoated triacetate film into the Indocyanine Green and hexamethylindotricarbocyanine dye solutions used for the grating preparation. The third was a filter described in the final report on the previous contract. It was prepared by dipping a piece of triacetate film into a solution of Acid Brilliant Blue DHN aggregated on a Carboset 511 polymer. This filter showed a broad absorption from the green region through the near infrared.

The bicolor filter with blue and infrared modulators gave disappointing results when tested with 2424. Both line directions could be recorded, but not at the same exposure level. The lines arising from the infrared grating appeared at lower exposures than those arising from the blue exposure. The bicolor filter with the two infrared modulators gave line structure in both directions and showed some discrimination when used to photograph the special transparency target. When the modulated imagery was examined under the microscope, however, the frequency of line breaks appeared to be high. The results were sufficiently promising for us to prepare a tricolor filter.

Tricolor Filter Tests. For the tricolor filter, we added a mixture of the cyan and magenta dyes as a third set of lines to go with the infrared bicolor filter. Exposure tests on 2481 indicated that the visible response was still negligible, that is, modulation lines were observed in the infrared directions at low exposure levels but, by the time evidence of line structure appeared in the third direction, the first two were already heavily overexposed. The visible band was then broadened to include the blue spectral region by using a mixture of the dyes Azure B and Spirit Yellow. The visible response still proved poor, and line structure on all the imagery was severely fragmented.

Further experimental investigation showed that we were troubled by two basic problems with these tricolor gratings. First, most imagery encountered under practical exposure conditions has a fairly broad infrared reflectivity. In other words, it is not likely to peak either between 700 and 800 nm or between 800 and 900 nm. Therefore, both infrared directions recorded the same information, and this caused the line fragmentation since the recording areas were the clear parallelograms between the intersecting infrared line patterns. Second, spectrophotometric measurements indicated that the Indocyanine Green absorption band was considerably broadened when dried down in a thin layer as in the grating. The overlap between the two infrared dyes was then too excessive to give good discrimination.

In view of the difficulty in obtaining infrared dyes with proper spectral bands and of the tendency of infrared reflecting objects to provide redundant information in two of the three bands, we decided to drop this approach.

BALANCED SENSITIVITY BY FILTER SELECTION

The remaining alternative to achieving an infrared color receptor based on current black-and-white infrared emulsions was to prepare balancing filters tailored to the film response curve. Since Tech/Ops has a facility for preparing dichroic filters that can be made to have sharp cutoffs and excellent rejection characteristics, we decided to prepare a dichroic sensitivity correcting filter. Ideally, the desired filter should be completely transparent in the green spectral region and should correct the relative sensitivity values of the red and infrared bands to the same level as the green. According to the data of Table V, a filter passing 40 percent of the red energy and 12.5 percent of the infrared energy was desired. A sequence of filters can be generated in one evaporation cycle, and the first sequence (shown in Figure 27) contained only one filter, 64A, with reasonable properties. The second set prepared (Figure 28) had two filters, 66A and 66B, with suitable characteristics. These filters were used for all subsequent work on the program.

Correction Characteristics of Dichroic Filters

Since we had baseline data on the photography of our standard color target, the first estimate of the effectiveness of the dichroic sensitivity correction filters was made photographically.

Exposure Tests. The color target was photographed outdoors on 2424 film using an unmodified Pentax camera with a filter pack consisting of a Wratten 12 and a dichroic correcting filter in front of the lens. Unfortunately, since the light level was lower than when we recorded the previous data, the exposure range had to be shifted. The film was processed as before, and the densities of each of the individual color patches were read on the Macbeth densitometer and tabulated. Although the data of Table VI cannot be correlated directly to those of Table II, the relative comparisons within each table are valid and can be used as an indication of color discrimination.

The data of Table VI show that the 66 series dichroics provide a slightly higher level of green response than the 64A dichroic. The spectral shift of the 64A filter toward the green is evidenced by the lower density values for the red patches. The increased level of green response can best be seen by comparing the density values for the blue (infrared reflector) and green (green reflector) patches. Where the blue patch generated at a given exposure level previously (Table II) had twice the density of the corresponding green patch, now the density difference is approximately 25 percent.

Since the 66A filter appeared to have the best three-color balance, it was used to assess the improvement in the ratio of visible to infrared sensitivity. The color target was again photographed on 2424 using two separate filter combinations, the Wratten 12 plus 66A dichroic for overall response and the Wratten 89B plus 66A for infrared response. The films were processed and evaluated as before. The data of Table VII indicate that the green response of the film is still overbalanced by its infrared

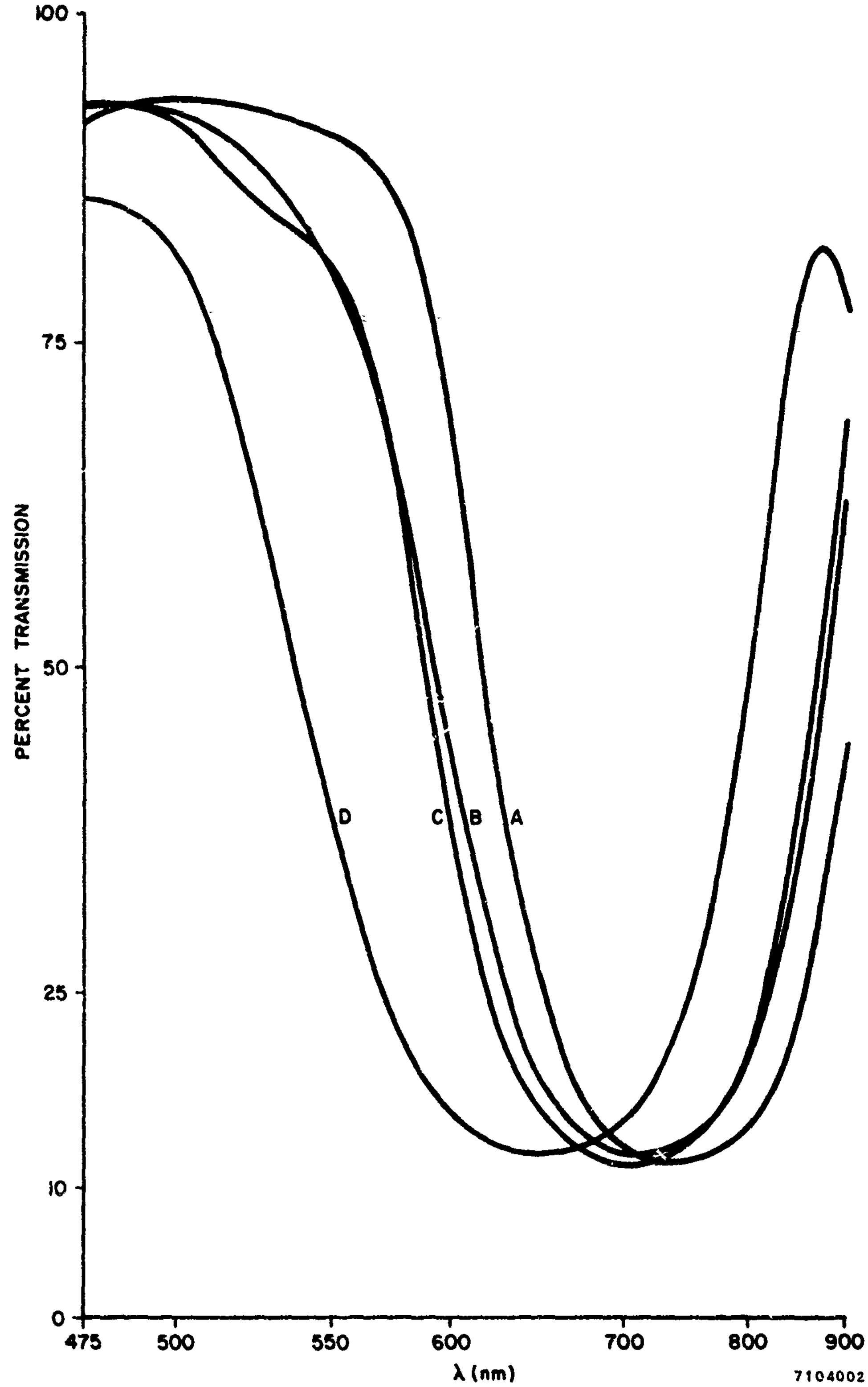

Figure 27. Spectra of First Generation Dichroic Filters (64 series)

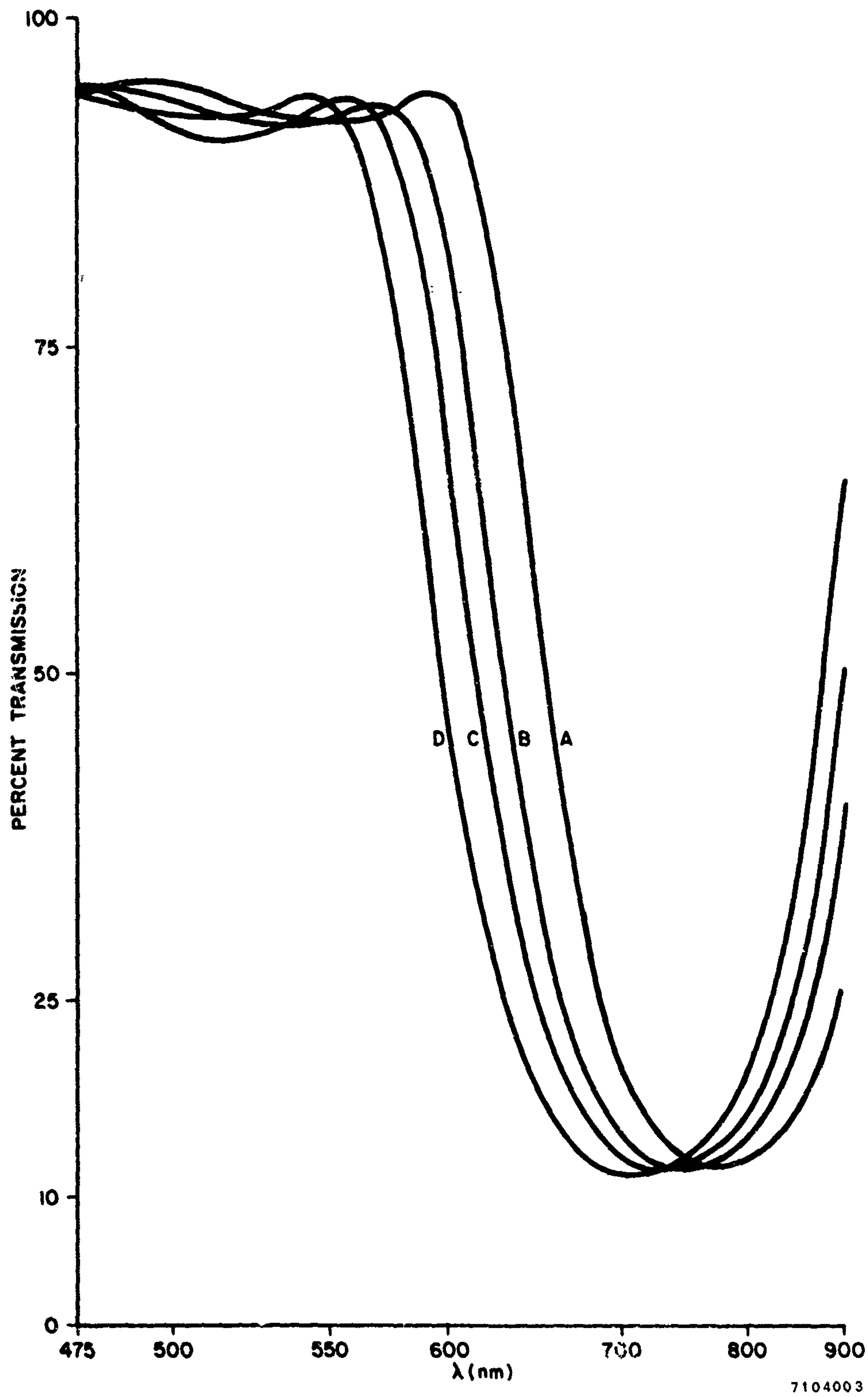

Figure 28. Spectra of Second Generation Dichroic Filters (66 series)

Table VI. Sensitivity Balancing Characteristics of Dichroic Filters

Exposure (sec at f/8)	Density of Green Patch			Density of Red Patch			Density of Blue Patch		
	64A	66A	66B	64A	66A	66B	64A	66A	66B
1/250	0.16	0.16	0.15	0.21	0.29	0.28	0.17	0.18	0.19
/125	.21	.23	.22	.36	.49	.45	.26	.29	.28
1/60	.31	.36	.36	.57	.75	.67	.41	.45	.45
1/30	.53	.60	.57	.90	1.13	1.01	.67	.74	.73
1/15	.78	.82	.82	1.23	1.46	1.35	.93	1.02	.97
1/8	1.22	1.36	1.26	1.68	1.88	1.72	1.45	1.50	1.46

Table VII. Relative Sensitivity of Dichroic Filter Corrected Infrared Film

Exposure (sec at f/8)	Density of Green Patch, 66A+		Density of Red Patch, 66A+		Density of Yellow Patch, 66A+	
	Wratten 12	Wratten 89B	Wratten 12	Wratten 25	Wratten 12	Wratten 25
1/250	0.12	0.12	0.25	0.19	0.28	0.17
1/125	.16	.14	.42	.31	.44	.30
1/60	.26	.20	.64	.48	.66	.45
1/30	.46	.35	.95	.76	1.01	.70
1/15	.67	.55	1.23	1.01	1.33	1.00

response. The red response is definitely improved, however, and the overall response, as measured by the yellow patch (which has almost equal reflectivity for all three colors), is also better balanced.

The improvement in balance between visible and infrared bands was confirmed by comparing the H and D curves generated by tracing (with a microdensitometer) the gray wedge images from the color target format for each filter set. Previously the curves did not separate, but the curves of Figure 29 indicate a relative log E displacement of 0.3, which is equivalent to a factor of 2 between overall and infrared response.

At this point, we proceeded to analyze the color separation characteristics of the filter-film combination by exposing 2424 to the gray wedge on the color target through the color separation filters of Figure 4. The film, processed as before, was examined; the wedges from the 1/15 sec exposures, which appeared optimum, were analyzed. The H and D curves of Figure 30, although influenced by flare fog resulting from light entering through the edges of the glass filters in the filter pack, indicate a great improvement in sensitivity balance over the uncorrected film curves of Figure 17.

The photographic results indicated that the second generation dichroic color balancing filters were probably a close enough approach to the ideal to warrant resuming tricolor grating tests. Before proceeding in this direction, however, we subjected the filter data to mathematical analysis.

Analysis of Potential Filter Combinations

The exposure tests suggest that the green band may still be out of balance with the other two. Before we proceeded to make a new series of dichroics, however, it seemed preferable to see whether any simple change in the filter pack would remedy the imbalance. The Wratten 12 is not an ideal minus blue filter for our system because it does cut some green sensitivity between 500 and 520 nm.

As alternatives we investigated the Wratten 4 and 8 filters and two yellow dichroic filters identified by the codes 9A and 41E. All these filters define a slightly broader band than the Wratten 12 and, in effect, extend the green region to a 460 to 470 nm limit. As the infrared film sensitivity begins to rise steeply below 500 nm, the added spectral breadth rapidly brings the green response into balance. For the 9E and 66A filter combination shown in Figure 3, the corrected film sensitivity curve has a relative area of 0.55 for the traditional 500 to 600 nm green band compared to an area of 0.85 for the red band. Thus a sensitivity imbalance would exist. Since the filter combination transmits an appreciable amount of energy to 470 nm, however, the added area increases the total to 0.81 and the green and red regions are now in balance. The combination of a Wratten 4

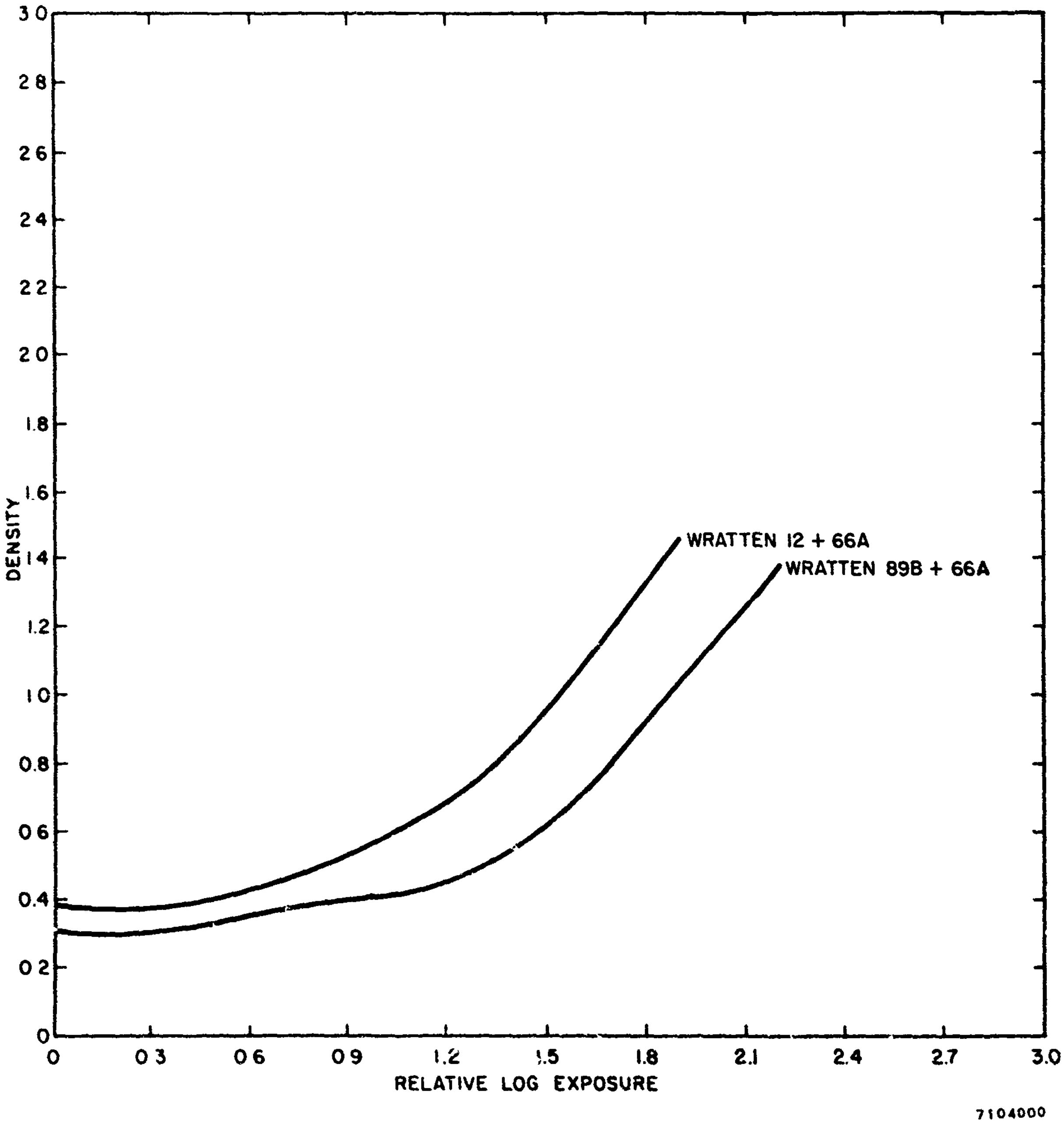

Figure 29. Comparison of Infrared and Overall Response of 2424 Infrared Film Corrected by 66A Dichroic Filter

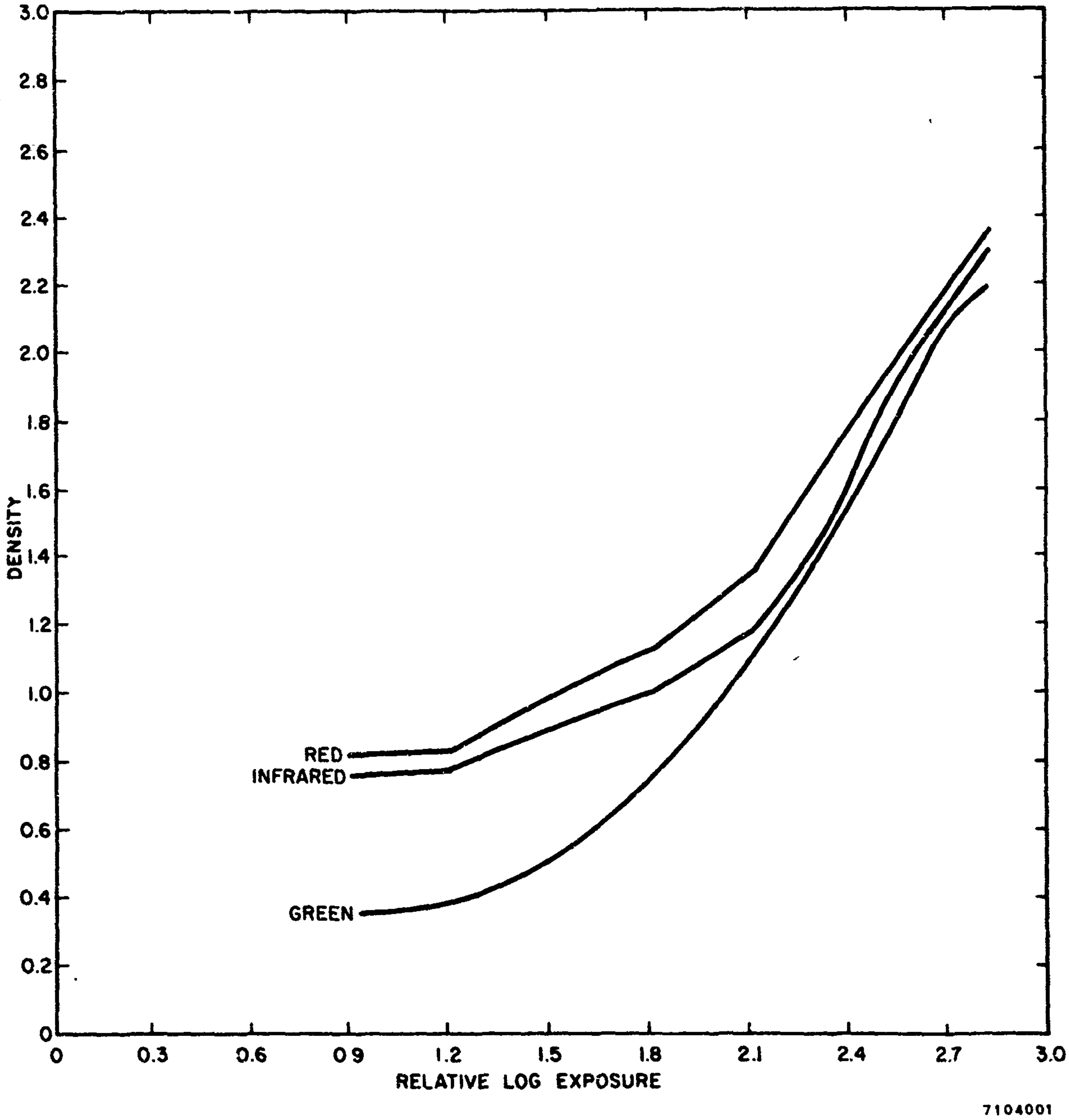

Figure 30. H and D Curves for 1/15 Second Red, Green, and Infrared Exposures of Gray Wedge on 2424 Infrared Film

and the 66A dichroic also gives a good balance. In this case the green band extends to 460 nm and the summed area values are

$$\sum_{460}^{600} = 0.93, \quad \sum_{600}^{700} = 0.92, \quad \text{and} \quad \sum_{700}^{900} = 0.73;$$

the three sensitivities should lie within half a stop of each other.

The calculations indicate that changing the minus blue filter will bring the green response into balance with the others, thus eliminating the need to prepare additional dichroic color balancing filters.

PERFORMANCE OF FILTER BALANCED FILM WITH TRICOLOR GRATINGS

To optimize our chances of achieving a successful result in recording color imagery on black-and-white infrared film, we decided to purchase a new master ruling to replace the 33 ℓ/mm master used for the earlier work. Accordingly, since it seemed advisable to operate at a slightly lower frequency, we settled on a 30 ℓ/mm carrier. The new ruling was used to expose patterns for a series of tricolor gratings coded 0-55-1, 0-55-2, and 0-55-3. The gratings of this series used the same dyes as previous gratings; the only difference between the members of the series was in the surface protection. Unprotected gratings scratch as the film moves across them in the camera, and the scratch patterns affect the photographic results. In this set the 0-55-1 grating had a layer of hardened epoxy resin on its surface, the 0-55-2 grating had a thin (0.4 mil) coverglass bonded to its surface, and the surface of the 0-55-3 gratings was left unprotected.

Before making outdoor exposure tests, we screened a series of red, brown, and related colored papers to see whether we could find one that would reflect red only, with little or no infrared contribution. The target designed for panchromatic films already had separate patches reflecting primarily green and primarily infrared, but nothing that could be used as a measure of a film's ability to record red. Ektachrome Infrared Aero film was again used as the standard for screening test patches, and we were able to find one giving a bright green false color response and one giving a dark, faintly bluish green. The red patch on our target was replaced by the lighter of the two patches, and the yellow patch was replaced by the darker. The remainder of the target was unchanged.

Photographs of the new target were taken on 2481 film. We used a TOC camera, and the film was in contact with the 0-55-1, 0-55-2, or 0-55-3 filter during exposure. The 9E and 66A dichroic filter combination was used in front of the camera lens to correct the film response. The films were processed for 8 min in D-19 fixed, washed, and dried. Examination of the negatives both under the microscope

and on the playback bench indicated that infrared and green exposures were recording properly. However, there was no hint of a green false color playback to indicate that we had successfully recorded red colors. Line structure in the red coding direction was weak on the negative over the entire exposure range. The playbacks from the three gratings were similar, and there was no difference in line structure between any of the negatives generated. This indicated that the separation between the grating and film caused by the thickness of the coverglass did not cause any deterioration in line quality. Since both the unprotected and epoxy-protected gratings exhibited scratch marks after the first set of tests, we concluded that coverglassed gratings were to be preferred in the future.

The inability of the infrared film to record red imagery was puzzling, especially since the calculations indicated that red sensitivity was slightly predominant in the corrected film response. The ability of the cyan dye of the tricolor grating to modulate red exposures was not in doubt since it was the same cyan used successfully with panchromatic and extended red panchromatic films. Actually, since we process to a negative, the line density produced on the film is a result of red light exposing the areas of the film between the cyan grating lines. The only interference in that region should arise from red light absorption by the magenta and infrared dyes. This naturally would weaken the effect of the red exposure and lead to a low developed density. Spectrophotometric traces obtained on dried films of the dyes prepared from the solutions used in grating manufacture produced the curves of Figure 6, which showed clearly that the overlap between the central red band and the two side bands was excessive.

To see whether we could obtain further information that would help us to evaluate the reasons for the observed grating performance, we determined the color separating ability of the 0-55 series gratings. The procedure used was to photograph two mounted gray patches differing in reflectance by a factor equal to half a stop. The TOC camera containing the grating and 2481 film was placed at a distance that allowed the two patches to fill a 35 mm frame. The 9E and 66A dichroic filters were used in front of the camera lens along with each of the color separation filters of Figure 4. The camera lens opening was f/11, and exposures were made over a log E range of 1.5. The film was processed in the usual manner and the characteristics of the modulated frames were determined in the diffractometer. Both the 0-55-2 and 0-55-3 gratings were analyzed to see whether the presence of the cover glass on the former would reduce its efficiency.

The data plotted in Figures 31 through 36 are essentially inverse H and D curves. In each figure, the upper curve was constructed from measurements of the undiffracted dc energy passing the film gate. It is a measure of the density obtained at each exposure level but, since the patch of the lightest density passes the most energy, the upper end of the curve corresponds to the toe region of a normal H and D curve. The lower set of three curves, in each case, was constructed by plotting against exposure the relative energy diffracted into each color channel. The difference in peak diffraction energy between the color being measured and the other two colors is an indication of the effectiveness of the color separation. The latitude of the

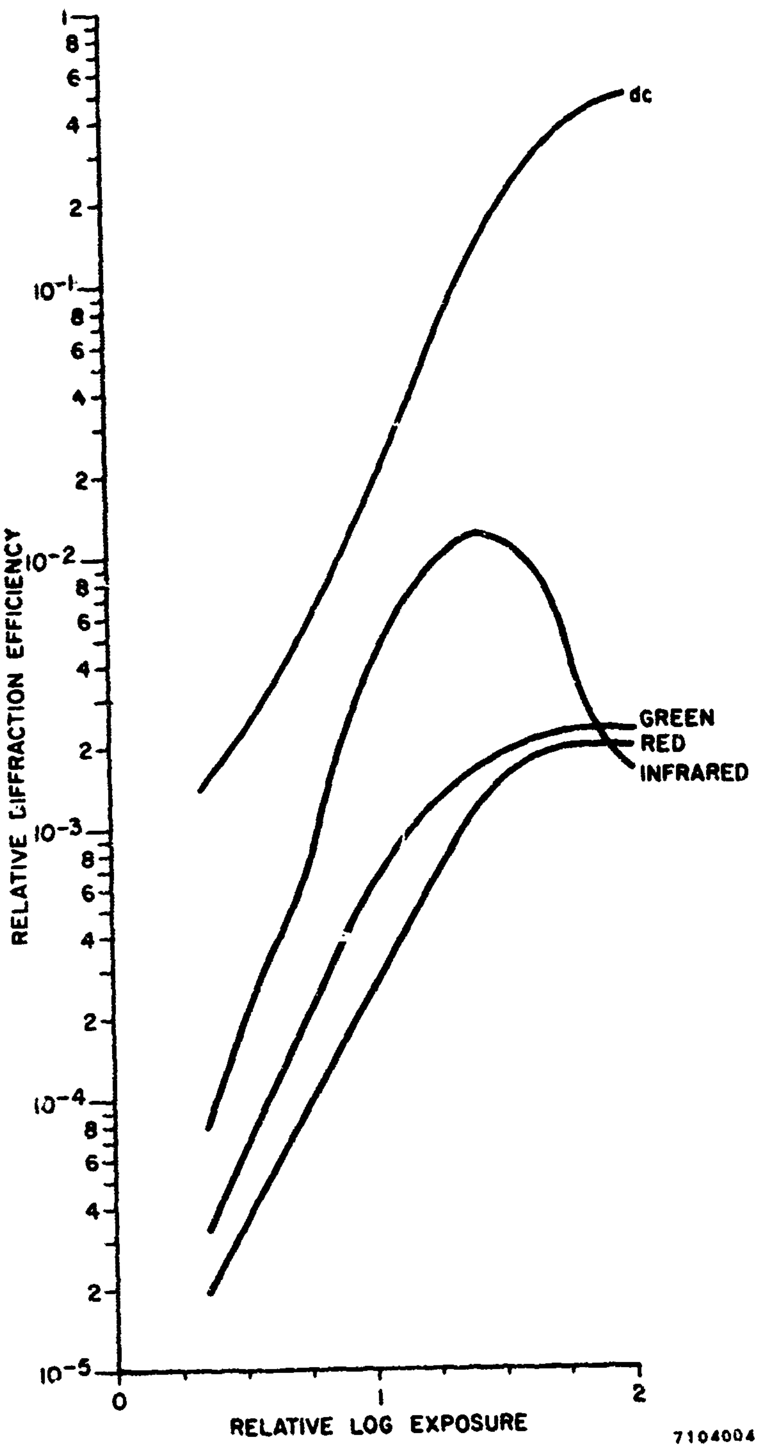

Figure 31. Infrared Color Separation Characteristics of Grating 0-55-2

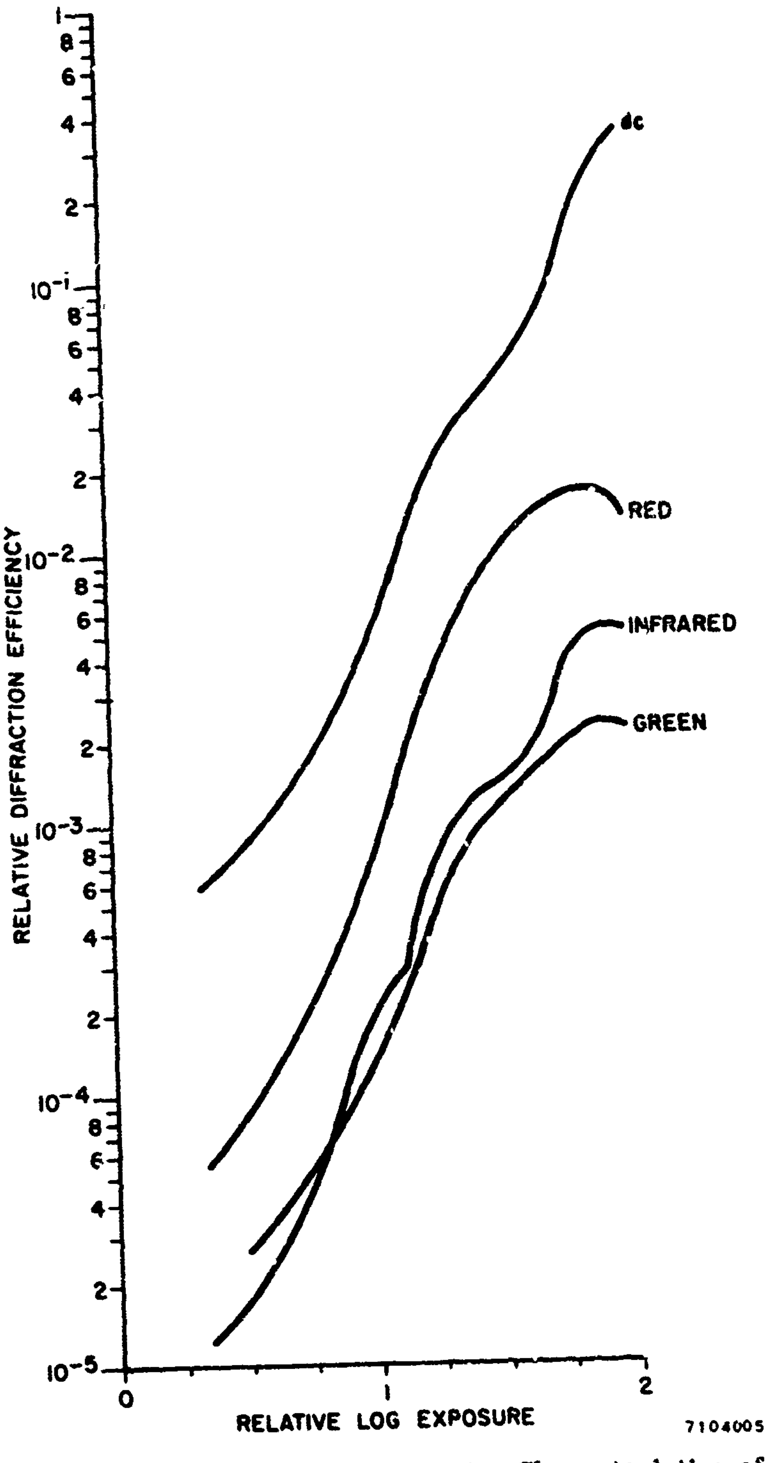

Figure 32 Red Color Separation Characteristics of Grating 0-55-2

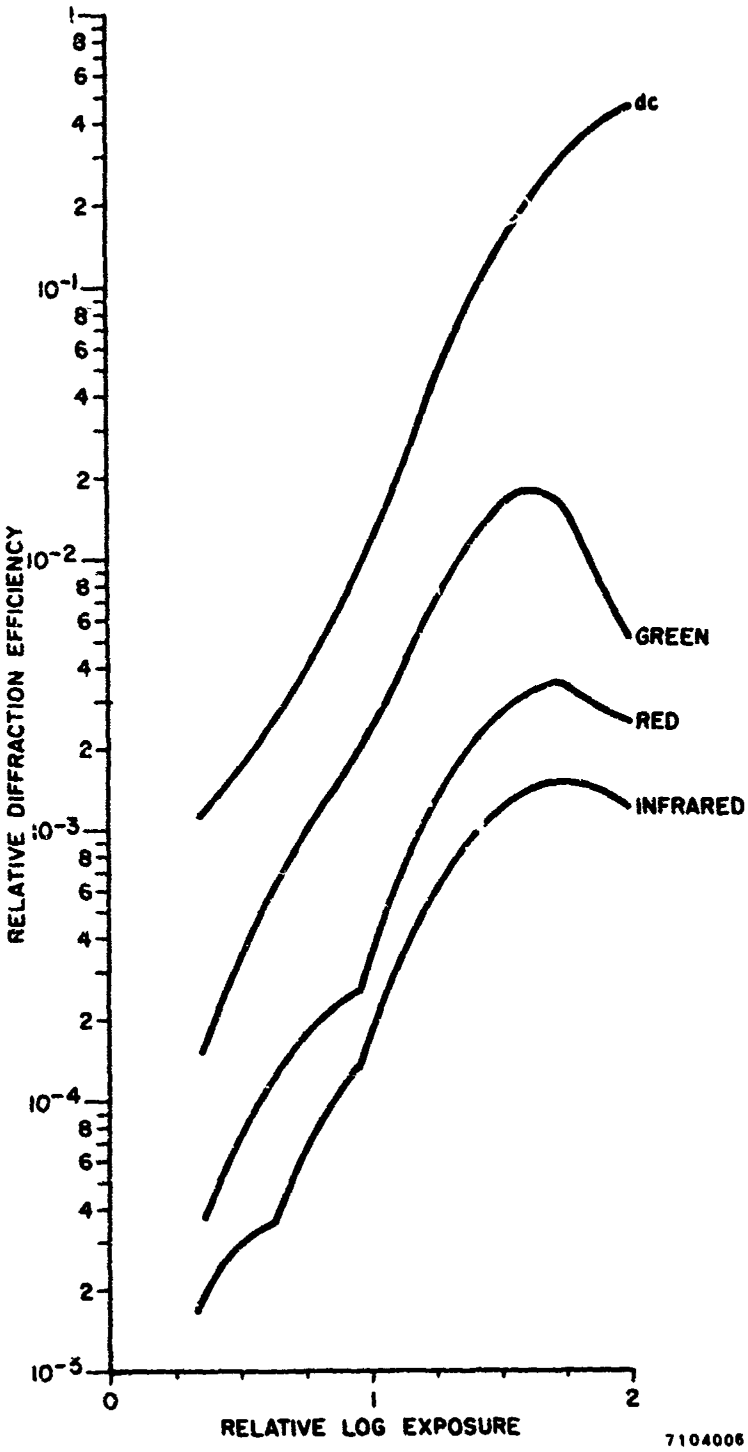

Figure 33. Green Color Separation Characteristics of Grating 0-55-2

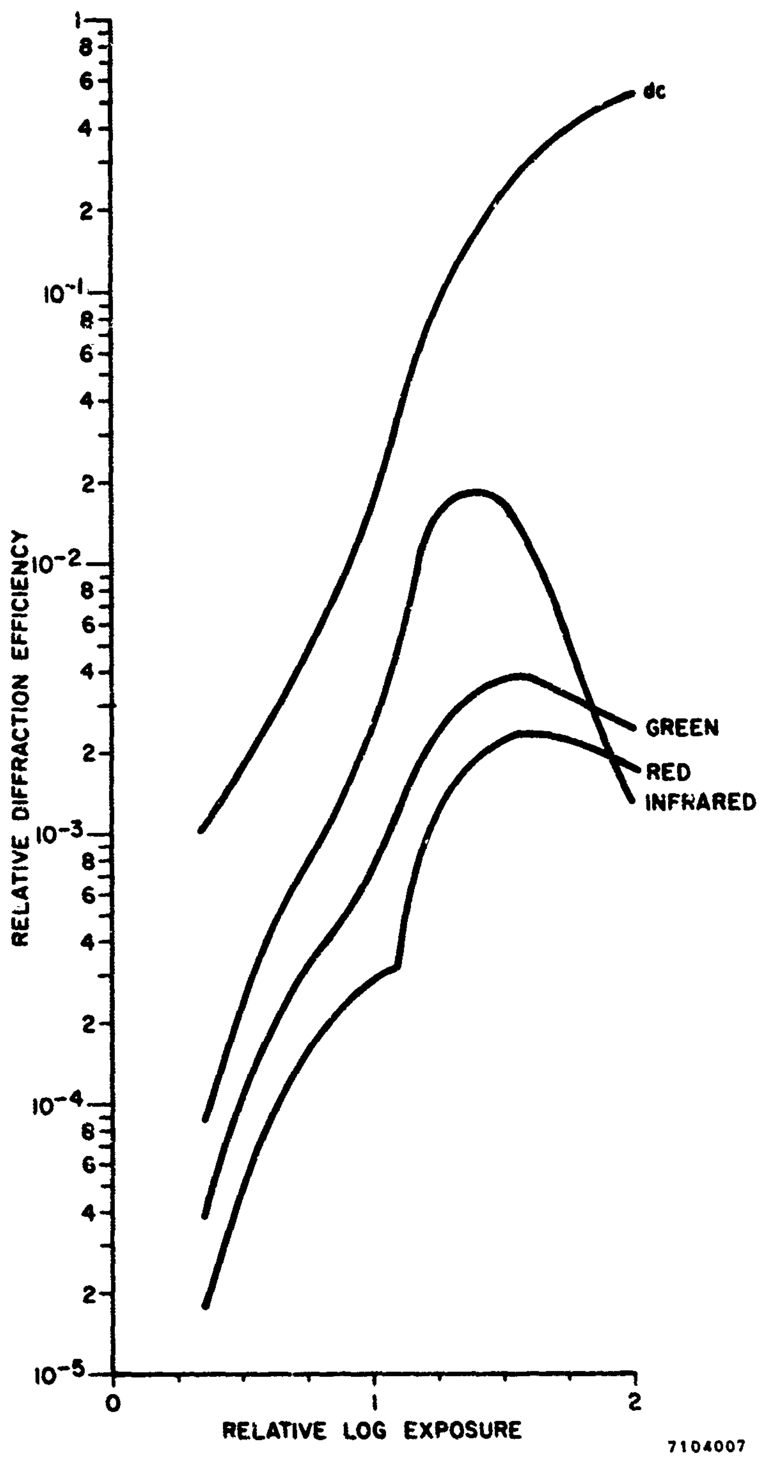

Figure 34. Infrared Color Separation Characteristics of Grating 0-55-3

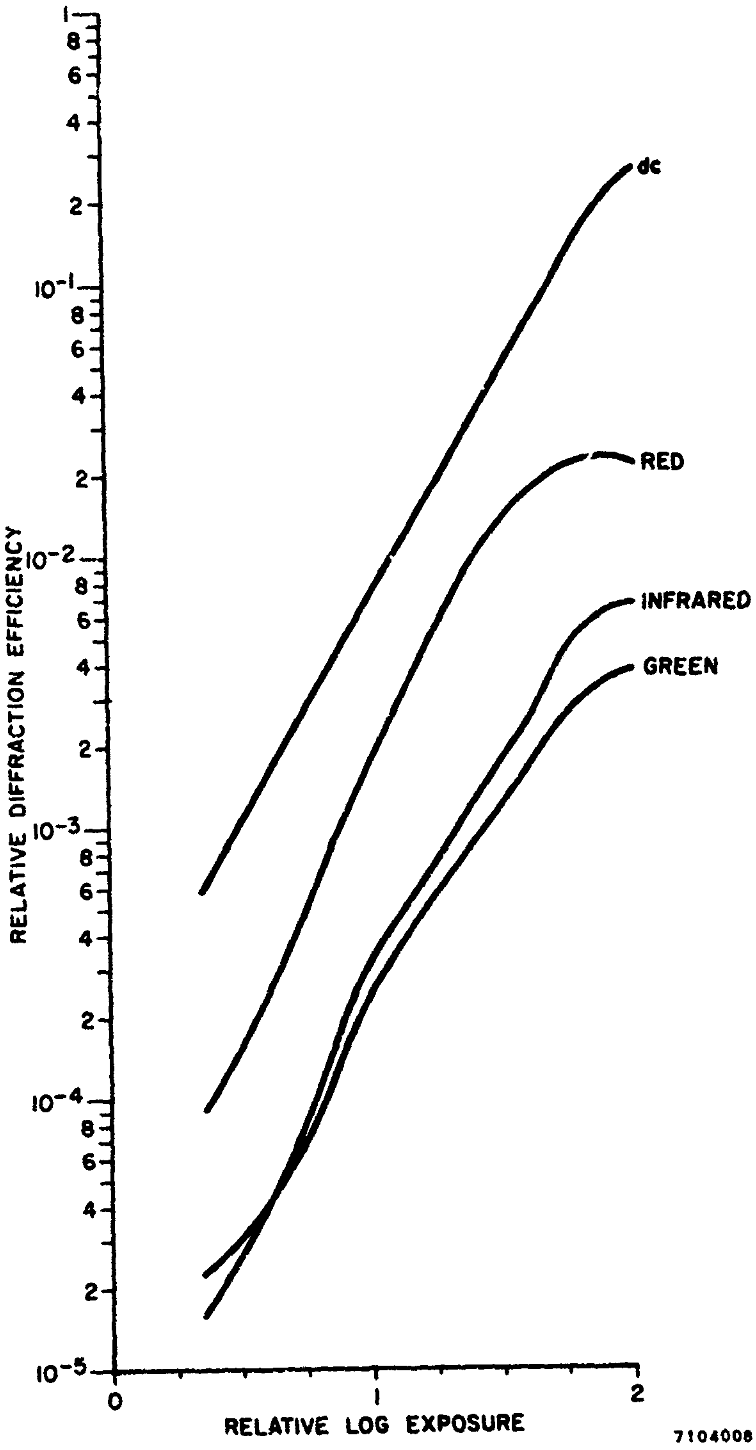

Figure 35. Red Color Separation Characteristics of Grating 0-55-3

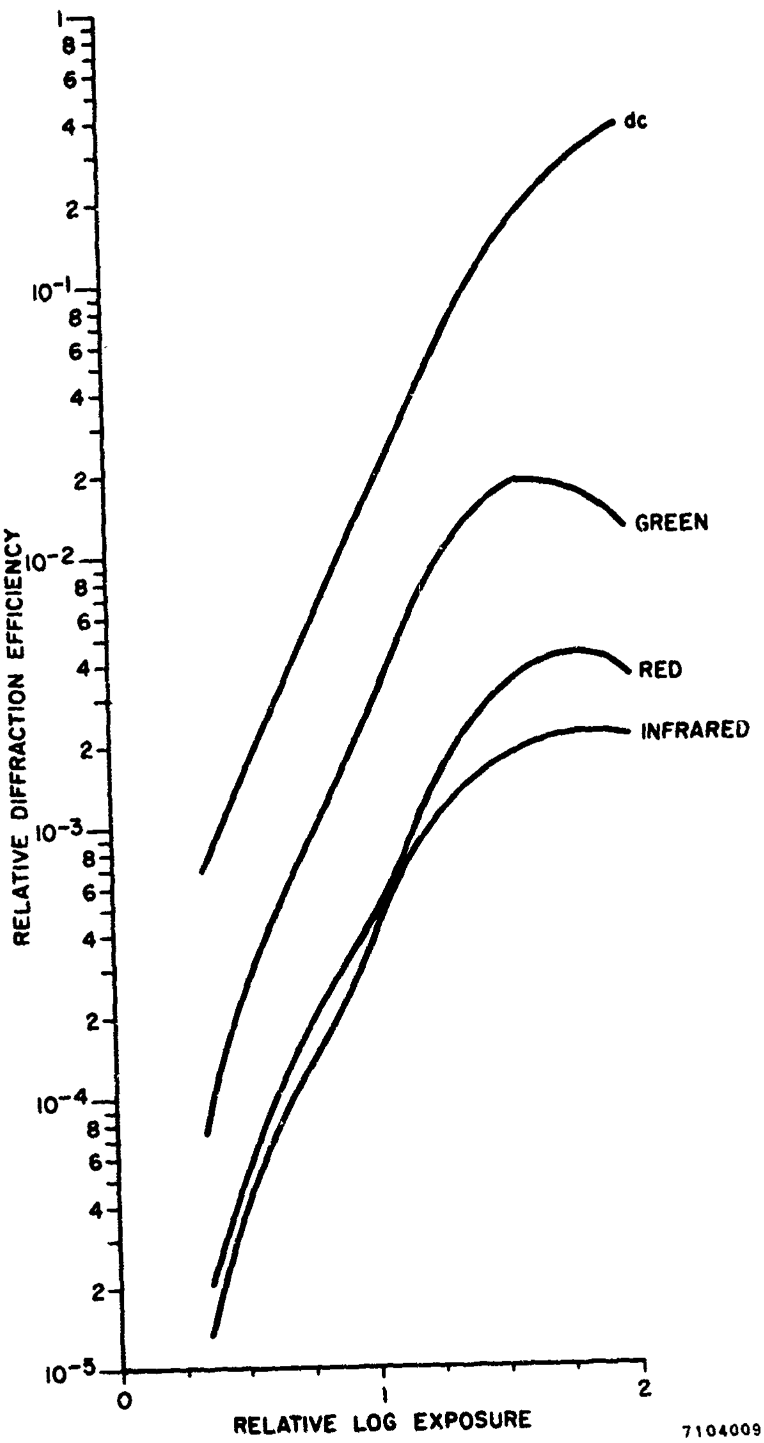

Figure 36. Green Color Separation Characteristics of Grating 0-55-3

black-and-white infrared films in our color recording system appears to be about two stops. Thus, a minimum of a factor of 4 is needed to ensure a separation of the individual colors. The curves for the 0-55 series gratings indicate that only the red separation falls below this factor. In all cases, however, the separation is close to the minimum. The separations for the 0-55-2 grating, if anything, are slightly better than for the 0-55-3 grating. Therefore we conclude that the cover glass does not reduce the effectiveness of the grating.

While the 0-55 series gratings were being tested, another set of tricolor gratings was being prepared. The only variation introduced was an increase in the concentration of magenta dye. Since we were spreading our green band into the blue, it seemed desirable to broaden the spectrum of the magenta dye to improve its ability to modulate in the 460 to 500 nm region. The new 0-58 series of gratings gave even poorer results than the 0-55 series. The color separation characteristics of this new series, exemplified by the data for 0-58-1 (Figures 37 through 39), clearly show the reason for their poor performance. Although we succeeded in improving both the red and green separations, the infrared separation was degraded to the vanishing point. Indeed, examination of the patches exposed through the 89B filter indicated that two sets of lines of almost equal density were present.

Since this series of gratings was prepared before our detailed analysis of the previous series indicated that our problems arose from the overlap characteristics of our dyes, and since increasing the magenta dye concentration would tend to worsen the overlap conditions, the results obtained are not surprising.

TRICOLOR GRATING OPTIMIZATION

The failure to achieve a three color recording and retrieval with the tricolor gratings led to a re-examination of our approach. The excessive overlap in the dye spectra appeared to be the cause of failure, and this was disturbing because it would be difficult to remedy. Although alternate magenta and cyan dyes are available and can be used to provide different spectral band properties, Indocyanine Green is the only available dye that even comes close to having the desired infrared band. (Actually it is inadequate in the sense that it provides poor coverage in the 850 to 900 nm region.) We decided therefore that two paths should be followed in a final attempt to prepare a workable tricolor grating. One, of course, was to improve the characteristics of the dyed gratings as much as possible. The other was to use Tech/Ops expertise in dichroic evaporations to prepare an all dichroic tricolor grating.

Alteration of Dyed Gratings

Close examination of the spectra of Figure 6 indicate that several changes are desirable. The magenta dye does not overlap into the red region, but the location of its absorption peak is above 550 nm. As a result, its coverage of the spectral region between 460 and 510 nm is inadequate. This drawback can be eliminated by

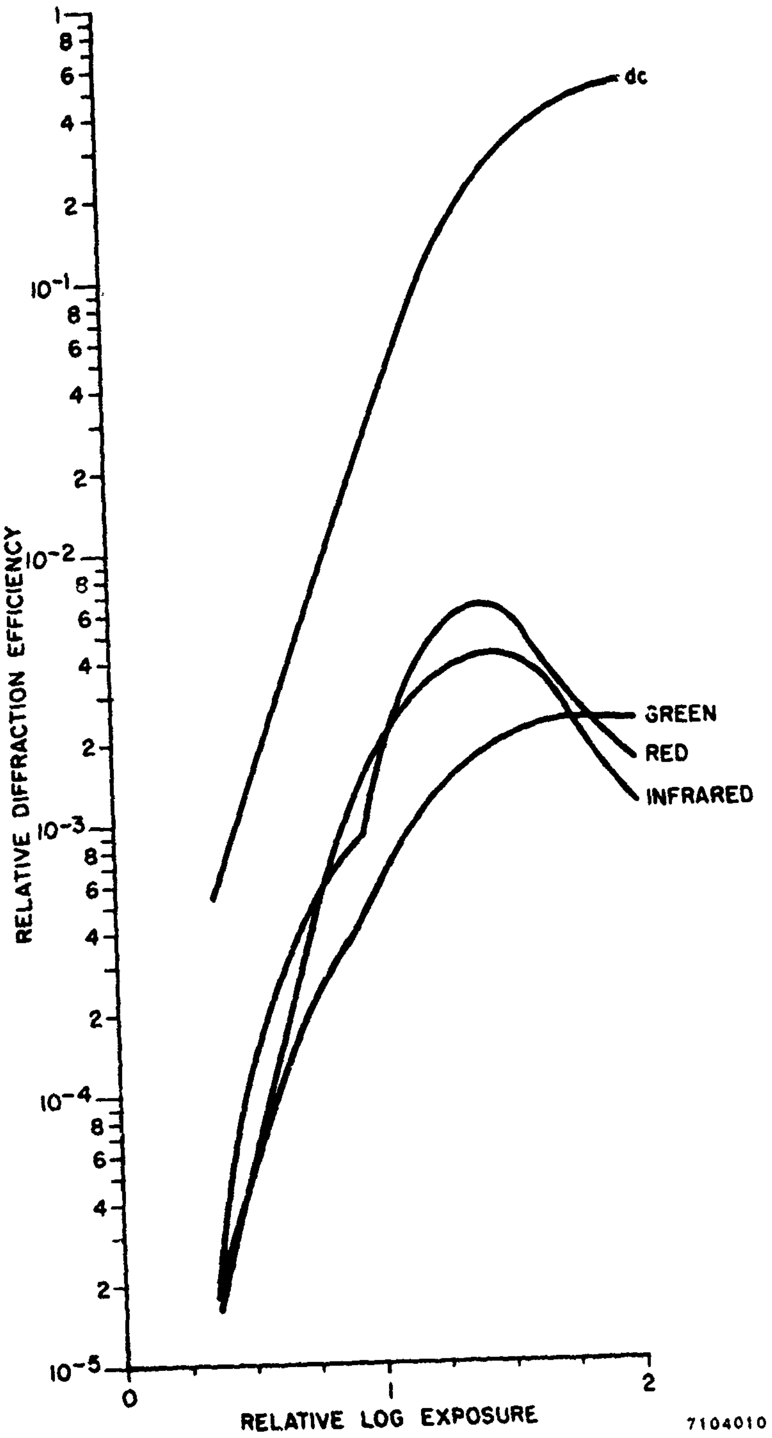

Figure 37. Infrared Color Separation Characteristics of Grating 0-58-1

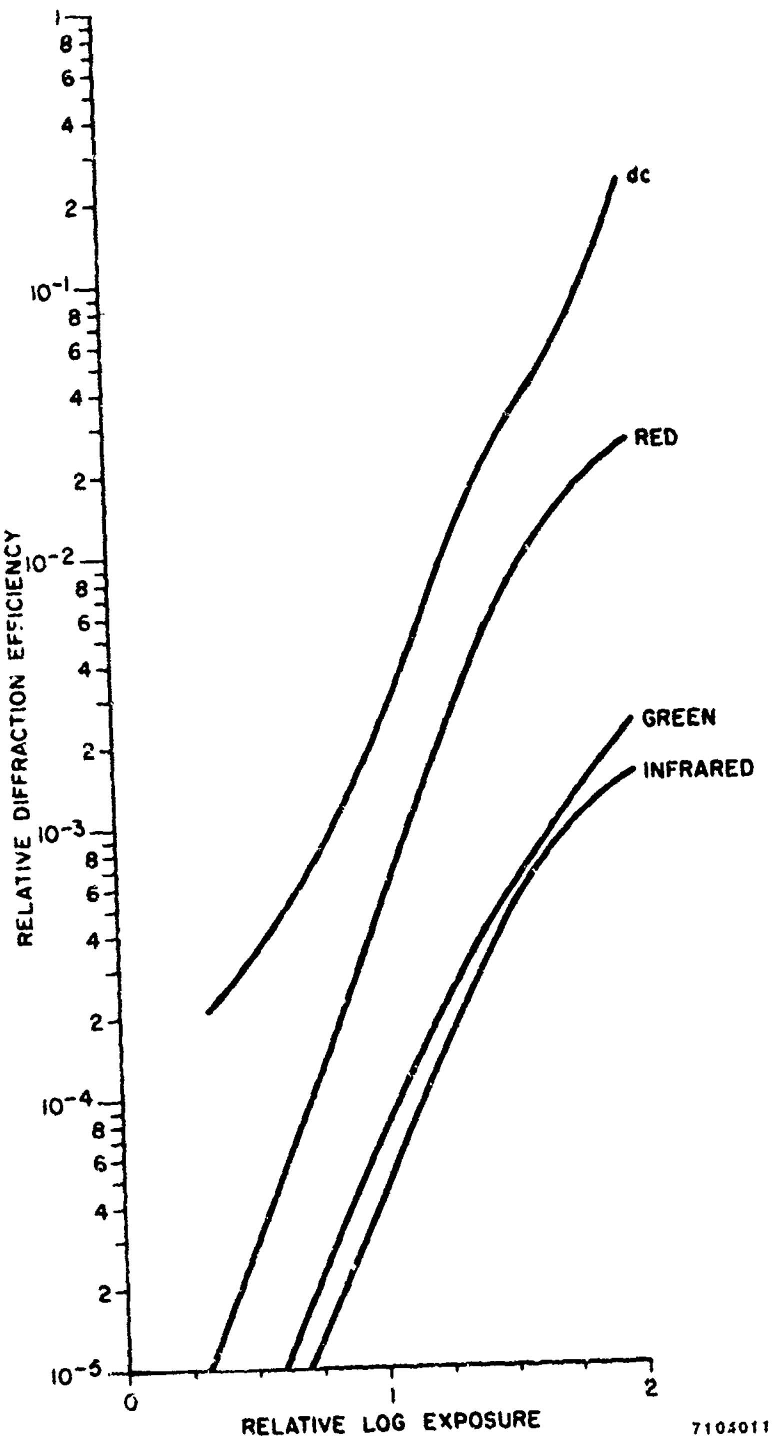

Figure 38. Red Color Separation Characteristics of Grating 0-58-1

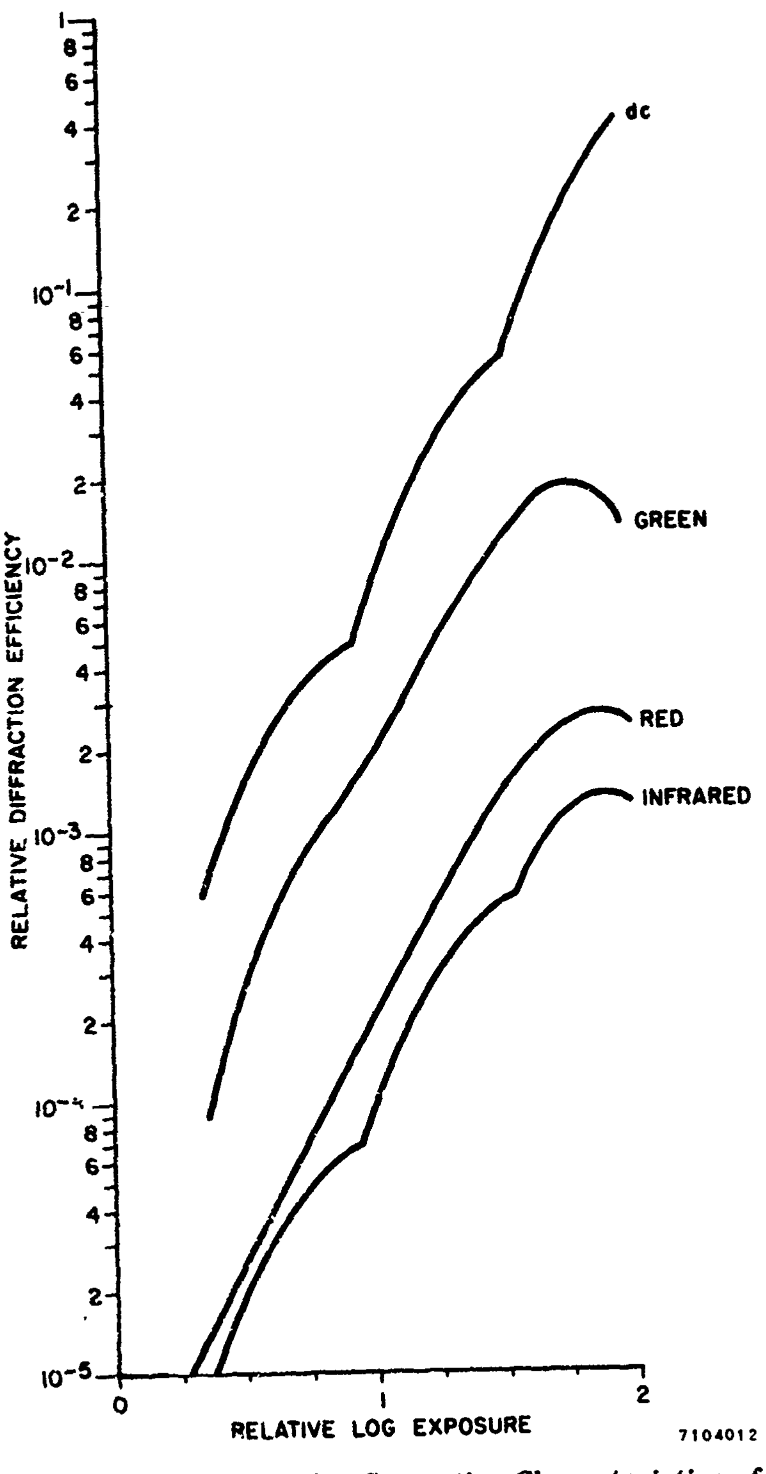

Figure 39. Green Color Separation Characteristics of Grating 0-58-1

mixing a yellow dye with the magenta. The characteristics of the yellow dye with respect to the blue sensitivity of the film are of little concern since we do not use any of the region below 460 nm. The dye Chrysoline N was found to be an excellent complement to the Sulphorhodanine B used as our magenta dye; the combination completely blanked out the 450 to 600 nm spectral region.

The cyan dye overlaps both side bands too strongly, and its spectral band must be narrowed. Although many alternate cyans are available, dyes used in the grating must withstand a baking treatment. Thermal instability eliminated a large percentage of the dyes tested. The spectral bands of the remaining cyans were too broad to provide the most desirable coverage in the 600 to 700 nm region. We were faced with the choice of decreasing the overlap on either the magenta side or the infrared side. The diffractometer data indicated that our main problem lay in the red-infrared overlap region; therefore as the best compromise we chose Alphazurine, a dye cutting sharply at 700 nm.

Indocyanine Green presented the most serious problem. Its minimum transmission was higher than those of the other two dyes. Thus, even in the region of its peak absorption it would not be as efficient at subtracting infrared energy as the other two dyes are at subtracting their respective primary colors. Because we were operating from a saturated solution of the dye there was little chance of increasing its absorption maximum. The broadening of its spectral band was a consequence of its high concentration in the dried vehicle that fills the grating lines. Our requirement for an even higher concentration made it unlikely that we could improve this condition. However, by experimenting with polymeric additives having charged substituents we were able to affect the state of aggregation of the dye and produce desirable shifts in its spectrum. The addition of nucleic acid to the dye-vehicle solution caused the dye spectrum to narrow and, at the same time, sharply increased the height of the absorption peak. Unfortunately, the spectral narrowing took place at both the short and long wavelength ends so that the blocking effects of the dye were decreased in the 850 to 900 nm region.

New tricolor gratings labeled 0-60-1, 0-60-2, and 0-60-3 were prepared. All of the changes discussed above were incorporated. The resulting spectral characteristics of the individual sets of grating lines are shown in Figure 40. A comparison with the curves of Figure 6 indicates that the area of the red-infrared overlap region has been cut in half, the blue-green region is now blocked better, and the area of red-green overlap has been slightly increased.

Evaluation of New Dyed Gratings

The 0-60 series tricolor gratings were installed in TOC cameras, and outdoor color target exposures were made in the usual manner. Two correcting filter combinations were used in front of the camera lens. In addition to the usual 9E and 66A dichroics, we used a 41E and 66B dichroic filter combination. Referring to the curves of Figure 28, we see that the 66B filter blocks slightly more red light than the 66A. Calculations had shown that, because "Air Photo Daylight" is

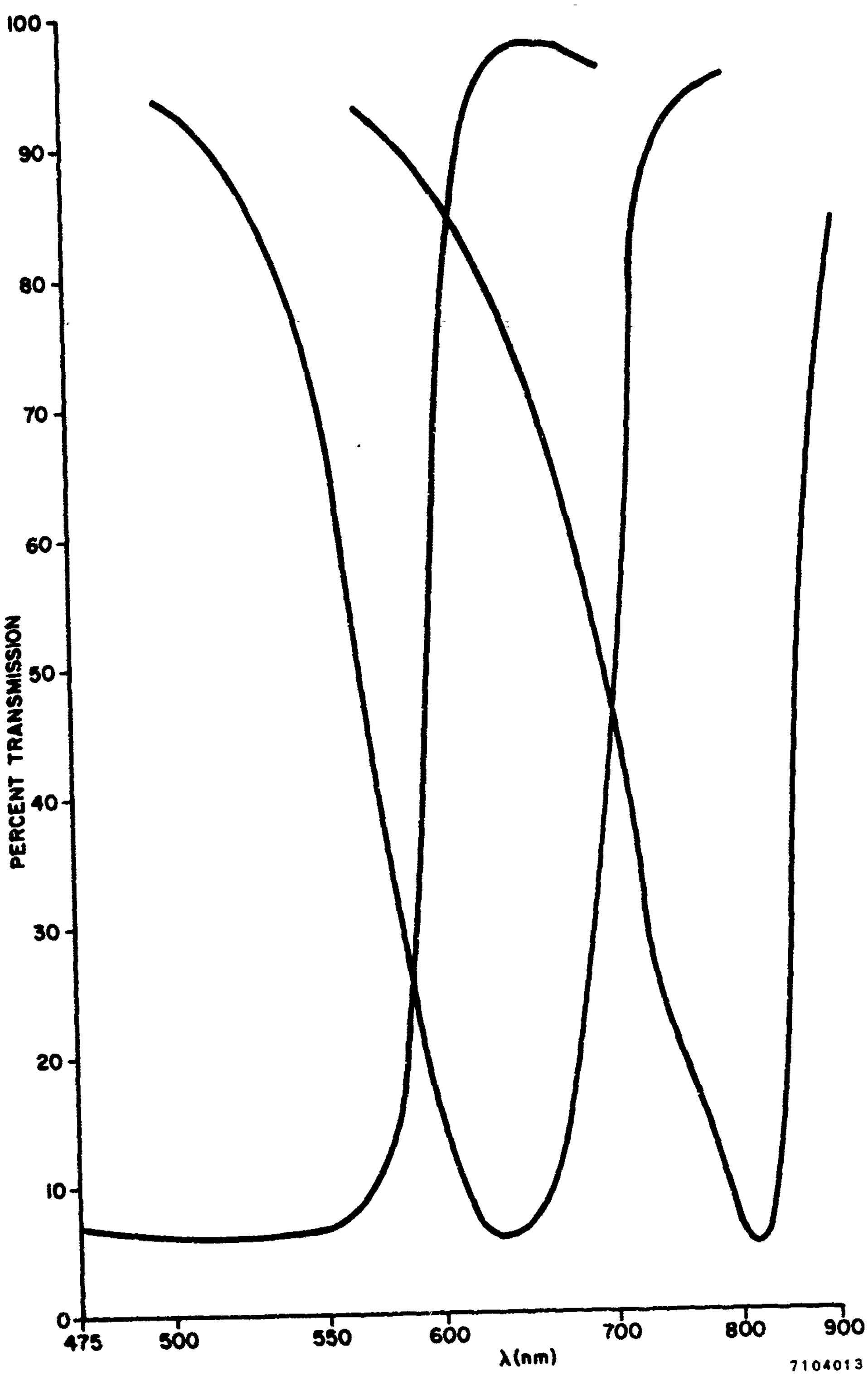

Figure 40. Transmission Spectra of Dyes Used in 0-60 Series of Tricolor Gratings

richer in red than in infrared, the red sensitivity of the 9E and 66A corrected film is greater than either the blue or infrared sensitivity. Reconstructions of the imagery from the negative showed that all three primary colors were present. The film frames exposed at ASA 40 and ASA 80 gave the best modulated imagery on the negative. To all appearances, an exposure midway between the two would have been optimum. The frames exposed through the 41E and 66B filter combination appeared to have slightly better color saturation than those exposed through the 9E and 66A dichroics. Positive transparencies were made from the four best frames by duplicating onto Kodalith Ortho, Type 3, and imagery showing the three false color primaries could be reconstructed from these transparencies. The colors did not have good saturation, and a high level of grain noise was evident.

Color separation properties were determined in the standard manner and the curves obtained for the 0-60-2 grating corrected by the 66B + 41E dichroic filter combination are shown in Figures 41 through 43. The curves appear to reflect the grating properties accurately. The red separation is good; the green separates well from the infrared, but not too well from the red; and the exposure range for the infrared was not sufficient to reach the maximum. The fact that the green separates poorly from the red is due to the increased overlap of the cyan dye in the green region. The infrared data, unfortunately, are incomplete because our supply of infrared film was exhausted. Additional film had been on order for two months but had not arrived by the time this report was completed.

The results obtained with the 0-60 series of gratings indicate that improvement of the red-green overlap condition could lead to a useful modulating filter. Further optimization of the color correcting filters may also help to improve color saturation.

Preparation of Dichroic Tricolor Gratings

Dichroic filters are prepared by vacuum evaporation techniques. By putting down alternate layers of transparent materials having high and low refractive indices and accurately regulating the thickness of these layers, the bandwidth and location of the minimum transmission can be regulated. The rejection (color blocking) characteristics of the dichroic increase as the number of layers increases. It is thus possible to make filters with sharp cutoff characteristics and increase their effective density without broadening the spectral band. With dyes, increased concentration not only causes spectral broadening but also often changes the location of the absorption maximum. The dichroics can be deposited in patterns, and we have been producing tricolor gratings by these procedures for quite some time.

The first filter with sets of dichroic lines having rejection maxima for red, green, and infrared light had the characteristics shown in Figure 7. Outdoor color exposure tests on 2481 film with this grating in the TOC camera and with either the 9E and 66A or the 41E and 66B filter combination in front of the lens gave results similar to those obtained with the earlier dye gratings. The false colors from both green and infrared exposures were present, but there was no evidence of a contribution from the red exposure. A second generation dichroic filter was prepared with the spectral characteristics shown in Figure 44. Even though the overlap was reduced and the bands were

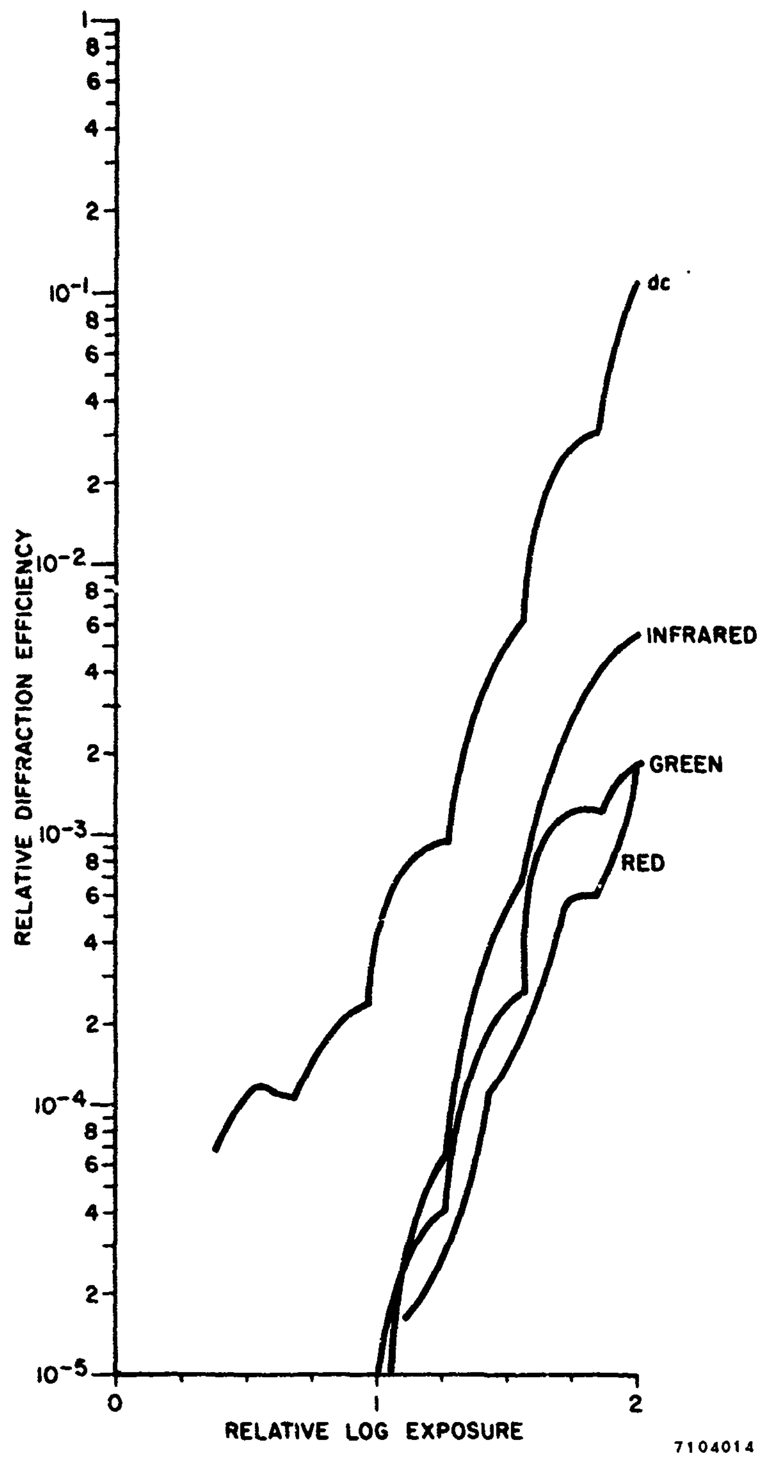

Figure 41. Infrared Color Separation Characteristics of Grating 0-60-2 with Correcting Filter Combination 66B and 41E

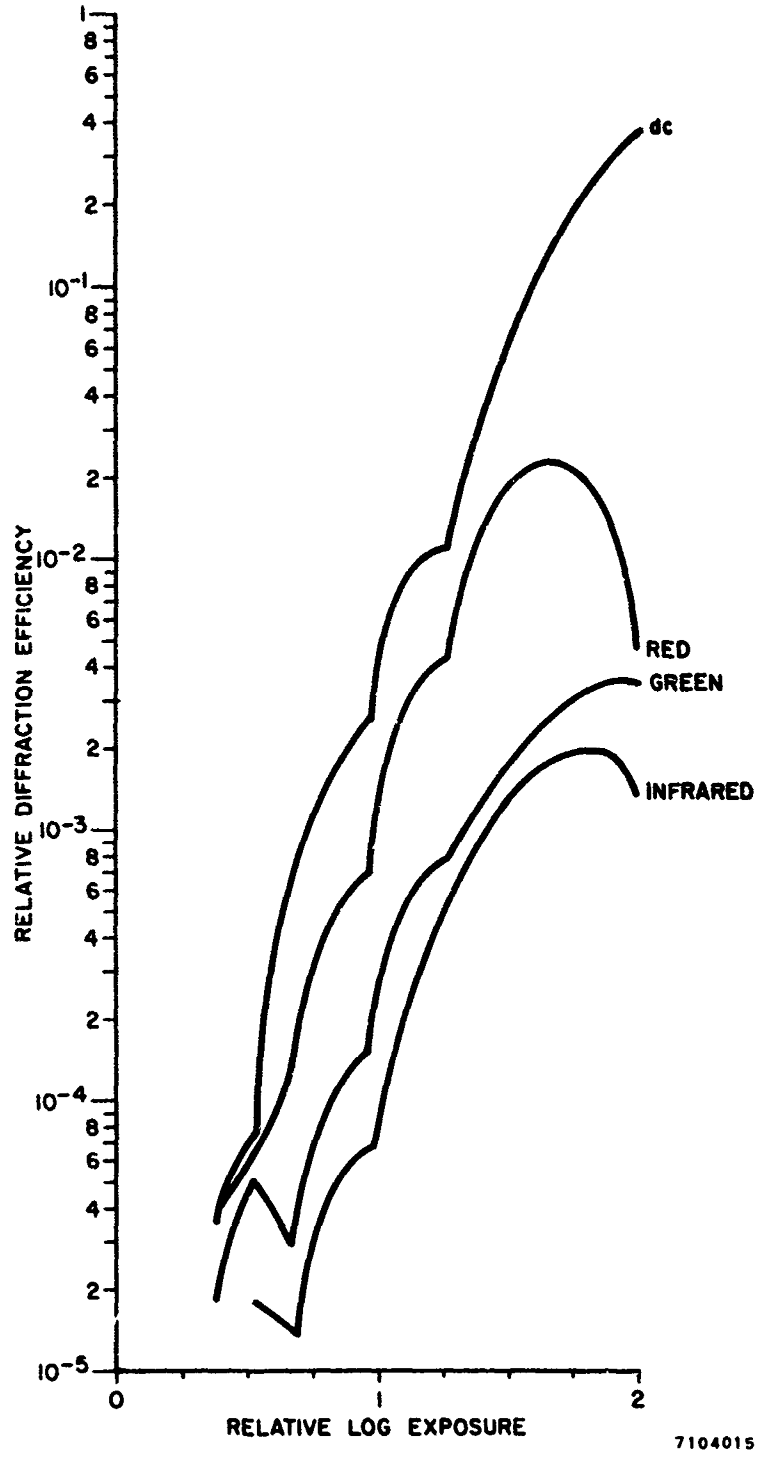

Figure 42. Red Color Separation Characteristics of Grating 0-60-2 with Correcting Filter Combination 66B and 41E

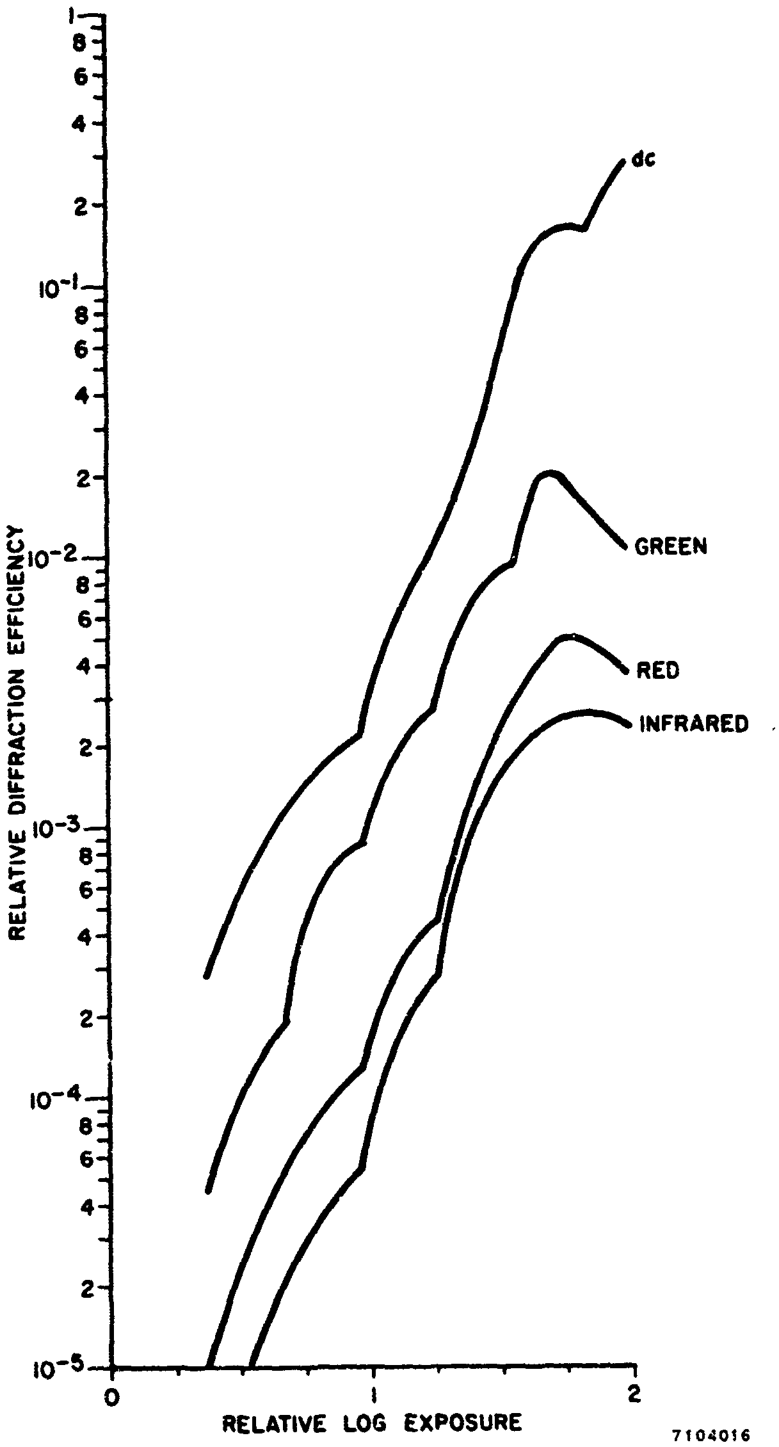

Figure 43. Green Color Separation Characteristics of Grating 0-60-2 with Correcting Filter Combination 66B and 41E

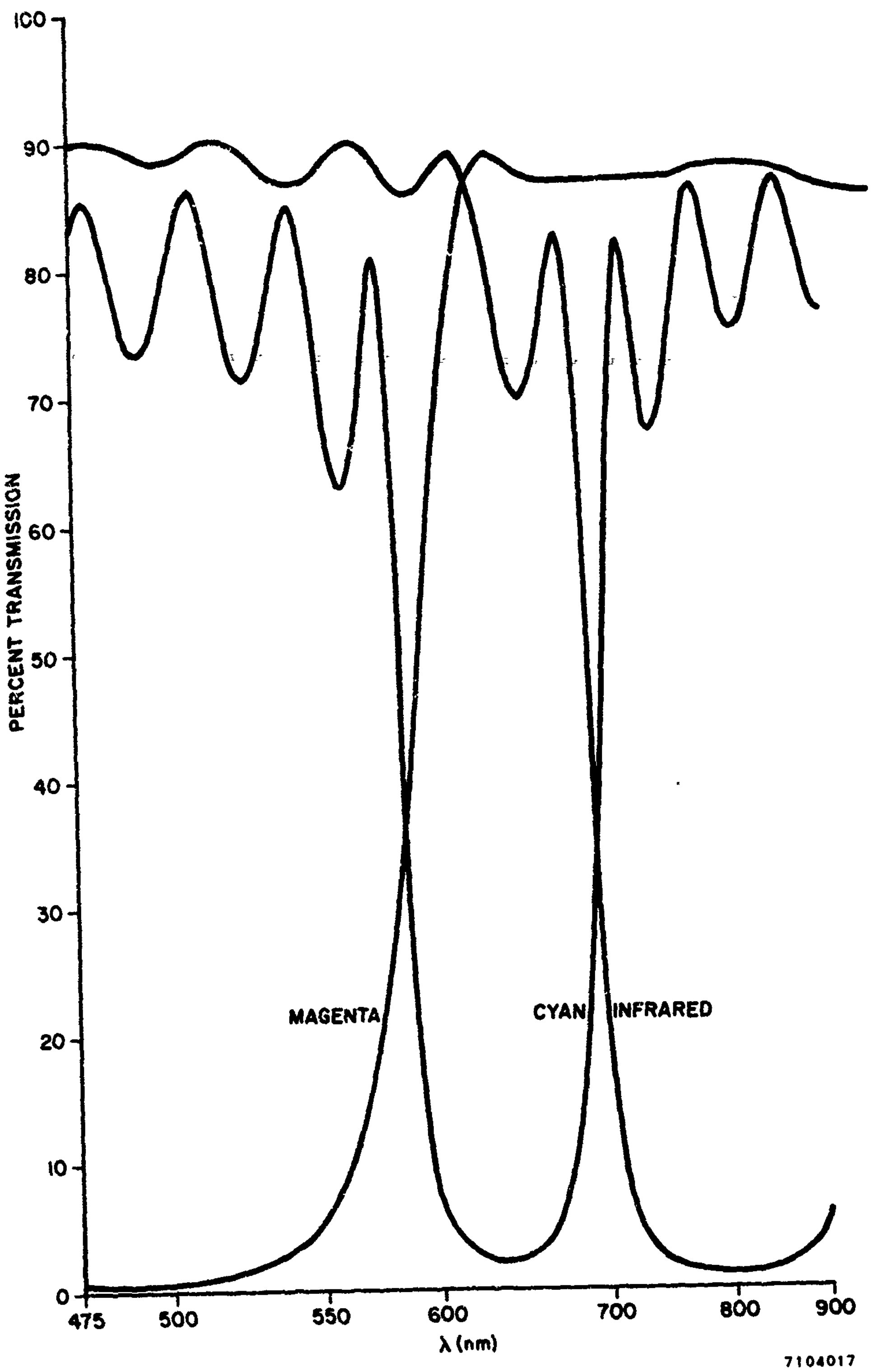

Figure 44. Spectra of Modulating Dichroics in Second Generation Dichroic Tricolor Grating

shifted slightly, we did not achieve the three color result obtained with the final dye grating.

The further analysis of the dichroic gratings to determine the cause of their poor performance was impossible because of insufficient time remaining on the program. Their properties may be much different from those of the dyed gratings. The exposure tests indicated that the speed level obtained with the dichroic tricolor gratings was a stop to a stop and a half higher than before. It is apparent that the limitations of current infrared films narrows the range in which we must operate to get a reasonable result. To really balance the film properly we must take into account the film sensitivity curve, the "Air Photo Daylight" curve, the transmission curves for the individual dichroic filters in the tricolor grating, and the transmissions of the available balancing filters. Until this has been done we cannot properly evaluate the performance of the dichroic filters.

SENSITOMETRIC INVESTIGATIONS

Sensitometric studies of the modulated imagery on the infrared film were hampered by several problems. In the early work the unbalanced sensitivity of the films did not allow us to record all three colors at the same exposure level. Later, as balance was achieved, the poor line structure and grain characteristics of the film complicated the results. The general basis of the most useful method of acquiring sensitometric data was presented in Section II of this report. As mentioned there, not enough effort could be diverted from the main problems of the contract to design a simple filter pack for correcting the output of Colortran lamps to an effective Air Photo Daylight and to find a selection of "neutral" patches (that is, ones having equal green, red, and infrared reflectivity) suitable for constructing a step wedge. Primarily our sensitometric experiments were confined to investigating the effect of various factors on the sensitometric procedure, particularly as they applied to the recording qualities of the infrared film.

Phase Image Contribution

The main difference between the old and new infrared emulsions is in their degree of hardening. Earlier investigations indicated that present films are so highly hardened that dye solutions will not penetrate them readily. We therefore sought to determine whether tanning reactions taking place during development would create any detectable phase imagery. A series of modulated patches was generated by exposing 2424 film, while in contact with a Ronchi ruling, to a flat field of light. A dichroic red filter was used over the camera lens to restrict the exposures to a single color band. The film was processed in the usual manner. The modulated frames obtained were analyzed in the diffractometer first in the normal mode, and then with a refractive index matching liquid (dibutyl phthalate) on the face of the emulsion. The liquid gate fills the phase ripples and prevents diffraction from them. The resulting diffraction efficiencies are compared in Figure 45. It can readily be seen that there is an appreciable phase contribution extending from the toe of the exposure curve over a 0.7 log E range. Although

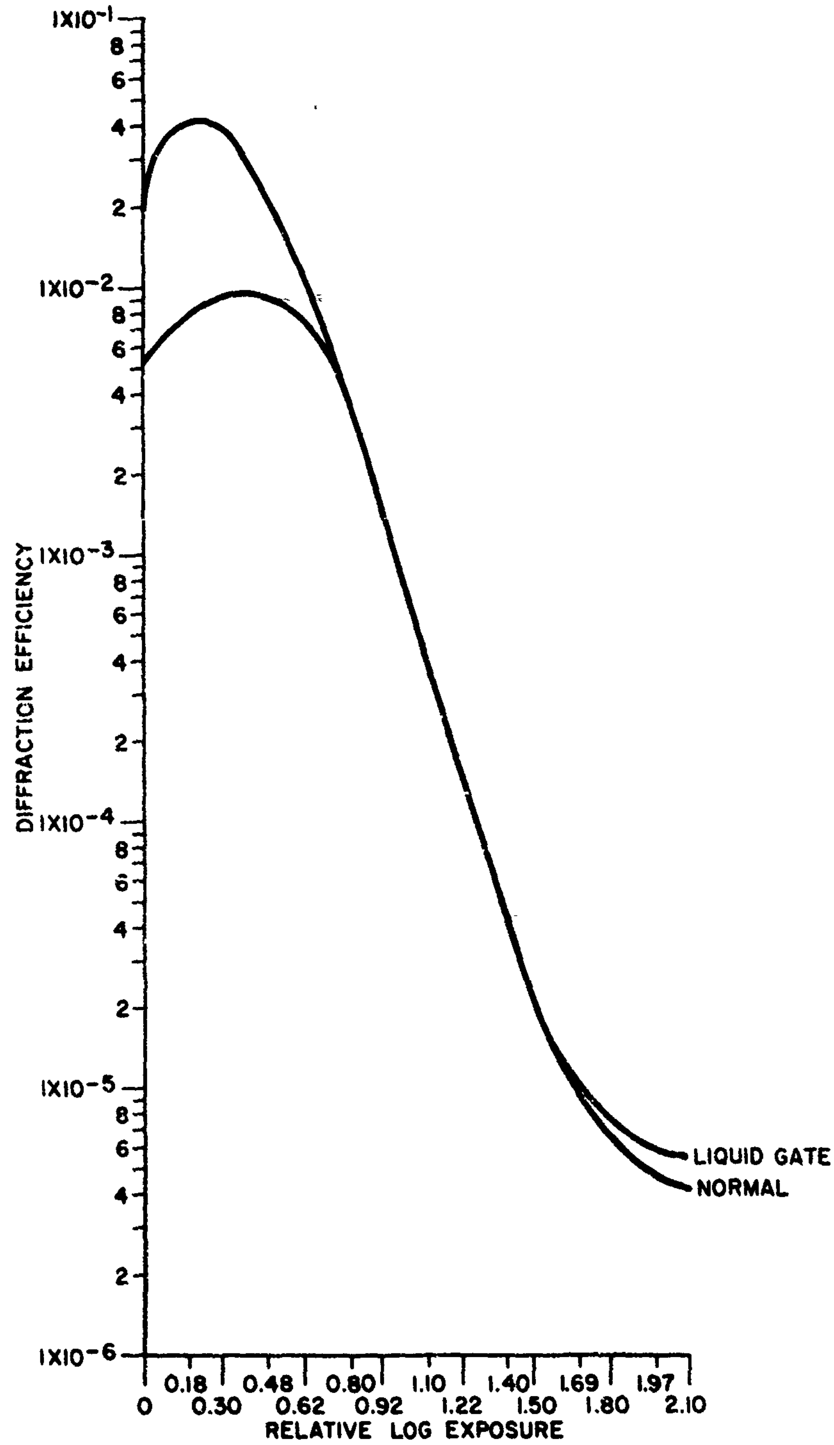

Figure 45. Contribution of Phase Image to Diffraction

the phase image may improve color saturation at low exposure levels on the negative, its influence does not survive the duplication step. Therefore, for more pertinent sensitometric data on the negative, a liquid gating procedure would be recommended.

Microsensitometric Procedure

To demonstrate the feasibility of using a reflectance wedge as a sensitometric standard we photographed the wedge image on the color target under conditions where it filled the 35 mm frame. Direct Positive Panchromatic film was held in contact with a tricolor grating designed for use with panchromatic materials. The wedge developed on the frame that appeared to have the optimum exposure was analyzed in the diffractometer. The system had to be modified slightly to restrict the size of the light beam impinging on the film gate so that it could be kept small enough to remain within the bounds of a single step. Measurements from which a curve could be constructed were readily made. Duplication was relatively simple and similar diffractometer measurements could be made on the duplicate. The main drawback to this type of evaluation lies in the small step size. When larger patches are photographed there is enough room to avoid areas where imperfections are present and to select more representative areas for measurement. Should a small patch contain an imperfection, it would be useless from an analytical standpoint.

MISCELLANEOUS STUDIES

Film Striping Attempts

On two separate occasions magenta and cyan inks were striped from 40 ℓ/mm cylinders onto 2481 film. The striped film was then exposed in contact with 30 ℓ/mm Indocyanine Green grating in a TOC camera and processed. No color was obtained from the negative on either occasion. Examination of the film indicated that no definite line structure was present. Small strips of the striped film were exposed through the 520 and 640 mm filters in the Tech/Ops spectral sensitometer and processed to see whether modulation was obtained. Again, the result was negative. This was surprising because on last year's contract some 5424 film had been striped at 40 ℓ/mm and measurable modulation was obtained. Two reasons can be advanced for this discrepancy. Either the quoted high contrast resolution values (89 ℓ/mm for 5424 and 80 ℓ/mm for 2424) represent a real difference sufficient to allow the higher resolution film to hold a 40 ℓ/mm carrier, or the hardened emulsion surface of the new films has poorer ink acceptance characteristics and, consequently, we print stripes of poorer quality.

Sensitization of Panchromatic Film to Infrared

Theoretically a film can be modulated in a spectral region where it is nominally "color blind" by selectively sensitizing the film in a ruling pattern. Since the high frequency gravure printing process used for film striping appears capable of depositing sensitizing dye in a controlled manner, we decided to see what level of sensitization could be obtained by immersing a panchromatic film in a solution of infrared

sensitizing dye. Accordingly, Direct Positive Panchromatic film was dipped in solutions of the dye S-916 (which imparts an infrared sensitivity to silver halide peaking near 840 nm) varying in concentration from 25 mg/liter to saturation, for a period of 1 minute and dried. Sensitometric exposures were made through an 89B filter in the Tech/Ops Spectral Sensitometer. Initially a 5 sec exposure produced approximately seven steps of the wedge. Exposures were also made through the 640 nm filter of the spectral sensitometer to monitor the effect of the treatment on the film's red sensitivity. Film samples dipped into the more highly concentrated dye solutions gained perceptible amounts of infrared speed but lost much of their original red sensitivity. Film samples dipped into the 25 and 50 mg/liter solutions produced the full twenty one step wedge after 5 sec exposure through the 89B filter and did not lose any sensitivity at 640 nm. The gain in the number of steps corresponds to a hundredfold increase in infrared response. However a rough calculation of the exposure level indicated that the infrared speed conferred by the treatment was equivalent to an ASA speed in the range between 0.01 and 0.1. Since the negative speed of Direct Positive Pan is 80, the level of sensitization reached was insufficient to warrant further work.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

At the completion of these investigations, it is apparent that color scene imagery can be recorded on current black-and-white infrared films at a speed of approximately ASA 60 and a resolution of 15 to 20 ℓ/mm. The recorded information can be recovered in grainy, weakly saturated color from a positive black-and-white transparency generated by duplication of the negative. The poor latitude of the system puts stringent requirements on the recording conditions. However, it is quite likely that, by redesigning our color-correcting filters and by carefully balancing dichroic type tricolor encoding gratings to narrower limitations defined by the film-filter-Air Photo Daylight product, results can be substantially improved. At best though, because of the poor quality of current infrared films, the imagery will not be comparable to that from TOC systems employing panchromatic films of moderate speed and low granularity.

On this basis we would not recommend thinking in terms of a striped infrared film until an emulsion with a better set of properties (sensitivity distribution, resolution, granularity) becomes available. At that time a first phase study should be made using tricolor gratings for color coding. If the color retrievals prove satisfactory under these conditions and film properties allow the use of a 40 ℓ/mm carrier, the main problem to be solved will be that of synthesizing an adequate infrared-modulating dye at a reasonable cost.

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